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USING SOUND TO MODIFY FISH BEHAVIOR AT POWER-PRODUCTION AND WATER-CONTROL FACILITIES: A WORKSHOP

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PORTLAND STATE UNIVERSITY
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PHASE II: FINAL REPORT

Edited by:

Thomas J. Carlson
Battelle
Pacific Northwest National Laboratory
Richland. Washington 99352
and
Arthur N. Popper
University of Maryland
College Park. Maryland 20742

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Bonneville Power Administration
Portland. Oregon
U.S. Army Corps of Engineers. Portland District
Portland. Oregon
Empire State Electric Energy Research Corporation
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Portland. OR 97208-3621

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Workshop Facilitators

Dr. Thomas Carlson
Pacific Northwest National Laboratory
Richland, Washington 99352

Nancy Peacock
Research Writing Editing
Seattle, Washington 98125

William Bridges
Freelance Court Reporter
Pendleton, Oregon 97801

Greg Nations & Karl Stahler
Barr Audio Visual
Seattle, Washington

Working Group on
Using Sound to Modify Fish Behavior
at Power-Production and Water-Control Facilities

Thomas J. Carlson
Pacific Northwest National Laboratory
Battelle Boulevard
Richland, Washington 99352
Currently with Army Corps of Engineers
Portland, Oregon 97208

Dennis Dunning
New York Power Authority
123 Main Street
White Plains, New York 10601

John Ferguson
Portland District
U.S. Army Corps of Engineers
333 SW First
Portland, Oregon 97208-2946

Sandra Meier
Empire State Electric Energy Research Corporation
5172 Western Avenue Turnpike
Altamont, New York 12209

John Nestler
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, Mississippi 39180

Ed Nunnallee
Northwest Fisheries Science Center
National Marine Fisheries Service, NOAA
P.O. Box 130
Manchester, Washington 98353

Gene Ploskey
U.S. Army Engineer Waterways Experiment Station
Bonneville Lock and Dam
Cascade Locks, Oregon 97014

Pat Poe
Bonneville Power Administration
905 NE 11th
Portland, Oregon 97208

Arthur Popper
Department of Zoology
University of Maryland
College Park, Maryland 20742

Expert Panelists

Neal A. Brown
Atlantic Applied Research Corporation
Burlington, Massachusetts 01803
Current address: University of New Orleans
School of Architecture & Marine Engineering
New Orleans, Louisiana 70148

Thomas J. Carlson
Pacific Northwest National Laboratory
Richland, Washington 99352
Current address: U.S. Army Corps of Engineers
333 SW First
Portland, Oregon 97208-2946

Michael H.G. Clegg
Simrad Osprey Ltd.
Campus 1, Science & Technology Park
Balgownie Road, Bridge of Don
Aberdeen AB22 8GT Scotland

Sheryl Coombs
Parmly Hearing Institute
Loyola University of Chicago
6525 N. Sheridan Road
Chicago, Illinois 60626

Dennis J. Dunning
New York Power Authority
123 Main Street
White Plains, New York 10601

Richard R. Fay
Parmly Hearing Institute
Loyola University of Chicago
6525 N. Sheridan Avenue
Chicago, Illinois 60626

Joan Ham
Consultant, Environmental policy / technology
6000 Anniston Road
Bethesda MD 20817

Mardi C. Hastings
Department of Mechanical Engineering
Ohio State University
Columbus, Ohio 43210

Frank R. Knudsen
Department of Biology
University of Oslo
P.O. Box 1051 Blindern
N-0316 Oslo, Norway

Paul H. Loeffelman
Energy Engineering Services Company
1270 Clubview Boulevard North
Worthington, Ohio 43235

David Mann
Department of Zoology
University of Maryland
College Park, Maryland 20742

John K. Menezes
Sonalysts Inc.
215 Parkway North
Waterford, Connecticut 06385-0280

Jeremy Nedwell
Subacoustech Ltd.
Chase Mill, Winchester Road
Bishop's Walthem
Hampshire SO32 1AH U.K.

John Nestler
U.S. Army Engineer Waterways Exp. Station
3909 Halls Ferry Road
Vicksburg, Mississippi 39180

Paul V. Novakovic
Energy Engineering Services Company
3750 Hacienda Boulevard
Ft. Lauderdale, Florida 33311

Gene Ploskey
U.S. Army Engineer Waterways Exp. Station
Bonneville Lock and Dam
Cascade Locks, Oregon 97013

Arthur N. Popper
Department of Zoology
University of Maryland
College Park, Maryland 20742

Olav Sand
Department of Biology
University of Oslo
P.O. Box 1051 Blindern
N-0316 Oslo, Norway

Carl Schilt
Richard B. Russell Water Quality Laboratory
Highway 72 West
Calhoun Falls, South Carolina 29628-0533

Carl B. Schreck
Oregon Cooperative Fisheries Research Unit
Oregon State University
Corvallis, Oregon 97331

Edward (Ned) Taft
Alden Research Laboratory Inc.
30 Shrewsbury Street
Holden, Massachusetts 01520-1843

Andrew W.H. Tumpenny
Marine and Freshwater Biology Unit
Fawley Aquatic Research Laboratories Ltd.
Fawley, Southampton SO45 1TW
Hampshire, U.K.

Contents

Executive Summary

A workshop on "Use of Sound for Fish Protection at Power-Production and Water-Control Facilities" was held in Portland, Oregon on December 12-13, 1995. This workshop convened a 22-member panel of international experts from universities, industry, and government to share knowledge, questions, and ideas about using sound for fish guidance. Discussions involved a broad range of indigenous migratory and resident fish species and fish-protection issues in river systems, with particular focus on the Columbia River Basin. Because the use of sound behavioral barriers for fish is very much in its infancy, the workshop was designed to address the many questions being asked by fishery managers and researchers about the feasibility and potential benefits of using sound to augment physical barriers for fish protection in the Columbia River system.

Background

The first "Sound Workshop," held in 1992 in Tracy, California, generated results that were interesting enough to motivate the Bonneville Power Administration to launch an evaluation of whether fish-protection systems using sound might aid restoration of critically declining Columbia River salmon stocks. The initial product of this research was a critical review of previous efforts to use sound for fish protection. This resulted in a collaboration between the Army Engineer Waterways Experiment Station and the Pacific Northwest National Laboratory to develop the rationale for a broader research effort, which became known as the Acoustic Technologies Program.

Much of the work on fish hearing has been done with fish not found in the Columbia River Basin. And because there is substantial variation among species in ear structure and function and fish hearing capabilities, it is not appropriate to extrapolate data on hearing capabilities and mechanisms from one fish group to another, such as from clupeids to salmonids. Unfortunately, for many years studies that looked specifically at salmon hearing and salmon response to high-frequency sound (>20 kHz) failed to produce definitive results. It wasn't until the development and application of infrasound (<50 Hz) that laboratory and field studies began to demonstrate startle and avoidance responses by salmonids to sounds.

Building on this new and suggestive data, the Acoustic Technologies Program has coordinated several investigations to fill the knowledge gaps about the acoustic environment of the Columbia Basin and about salmon hearing. These include a baseline study of the morphology of the inner ear of Pacific salmon; tests of the reactance of steelhead to infrasound; and a full-scale test of the guidance effectiveness of a low-frequency sound system at Bonneville Dam on the lower Columbia River. The present workshop was designed to provide an information-rich forum of experts whose shared knowledge and experience would hopefully accelerate the learning curve in fish bioacoustics, for Columbia Basin applications and beyond.

The workshop structure

This second workshop was co-sponsored by the Bonneville Power Administration, the Portland District of the Army Corps of Engineers, and the Empire State Electric Energy Research Corporation (ESEERCO), a consortium of northeast utilities. Their collaboration–spanning many disciplines, diverse fish-protection issues, and local conditions at an array of water-control facilities across the country-indicates not only the wide-ranging interest in

acoustic technologies for fish protection, but also the desire to work together to expand the knowledge base about fish and sound and thereby bring the use of these emerging technologies out of its infancy toward fuller development and maximum efficiency.

The cross-disciplinary nature of bioacoustic science and system applications drove the selection of the 22 experts from diverse disciplines for this workshop. A sampling of their disciplines includes fish biology, fish physiology, and behavioral fish ecology; underwater acoustics; fish bioacoustics; acoustic ecology; mechanical and biological engineering; naval architecture and marine engineering; biophysics; auditory psychophysics; and comparative and evolutionary biology of hearing.

Given the breadth and scope of the knowledge and experience base on fish and sound, two crucial goals of the workshop were to begin to (1) consolidate and communicate the interdisciplinary knowledge base about underwater acoustics and the mechanisms of fish hearing and (2) clarify the state-of-the-art in acoustic system design, development, and application. Discussion was bounded within the framework of

- what is known and not known about the acoustic environment of fishes and the mechanisms of fish hearing, particularly for salmonids;
- the lessons learned from case studies of a broad range of experiments and applications of sound-deterrence systems,
- the critical uncertainties that currently limit confidence in sound-deterrence systems and restrict their application for protection of Pacific salmon and other fishes in the Columbia River Basin,
- the most promising research strategies to resolve those uncertainties and to more rapidly communicate new learning among researchers, fishery managers, and their constituents, and
- application of new and refined knowledge to the development of acoustic systems that successfully direct fish movement away from areas where fish are at risk from injury.

The workshop was organized into three sections.

(1)

A tutorial session covering the physics of **underwater sound, the morphology and physiology of the fish hearing system, and the behavioral response of fish to sound, emphasizing within- and between-species differences**

Following are some of the important issues that came out of these tutorials

- We must better understand what fish ‘listen to’ in their environment. Do they listen only to selected sounds or the general auditory scene where they develop a sense of the whole environment around them (just as humans use background sounds to get an impression of their environment)? What is the hearing band-width of different species, and how can we use that information to design acoustic mechanisms to potentially control fish behavior and movement? Will the 'control' sound be heard in the presence of large amounts of background or masking noise?

- Sound localization :is a highly relevant issue for fish passage, but we have very little data on how fish determine the position of sound sources in the environment around them, including the location of predators or prey. Obviously, if a fish cannot discriminate the position of a sound source, it cannot reliably swim towards or away from that sound. Studies to answer these questions, however, are technically difficult and not conducive to work in tanks because the acoustic environment even in large tanks is very complex and usually does not permit experimentors to accurately predict or measure the sound field stimulating the fish.

- There are important questions about age-related changes in the hearing abilities of fish. If fishes hear differently as they mature, it may mean that adult salmon, Z-year-old salmon, and smolts may not hear the same thing. We have no data on growth and changes in the ear or hearing of salmonids of different ages. This could wind up being critical to controlling their behavior with sound.

- Understanding the effects of long-term exposure to sounds on the sound-detection systems of fish is extremely important if we are to continue to use sounds to control fish behavior. Long-term exposure to sounds of even medium intensity may result in damage to the sensory cells of fish. If this is further demonstrated in salmonids and clupeids, it could mean that there is a very deleterious effect on fish survival both in the short- and long term.

- We need to address the problem of extrapolation of data from one species to another. Although data on hearing function and capabilities are available for fewer than 100 of the more than 25,000 extant species of fish, even this limited sample suggests significant interspecific variation in hearing capabilities. Thus, great caution must be taken in extrapolating,, particularly between species of different higher taxa and perhaps of different genera.

(2)

Case studies of applications of sound systems to fish-protection problems in the United States, the United Kingdom, and Europe.

There are successful applications of sound to repulse fish from regions of high risk near both hydropower and nuclear power plants. The species of fish for which effective stimuli have been identified and stimuli delivery systems have been developed at industrial scales are alosids, herring, alewives, and shad. In the case of salmonids, recent laboratory and field research has identified effective stimuli, and prototype stimuli-delivery systems are being tested. Successful identification of stimuli that elicit repeatable behavioral responses from salmonids and alosids seems to be expediting the search for stimuli for other species as well.

Successul applications of sound, either alone or as part of a system of physical and operational measures to prevent fish from entering regions of high risk, share a common approach. The first element of this approach is to understand the physiology of the hearing systen of the fish of interest. Next, based on an understanding of the fish's hearing system and hearing capabilities, carefully conducted tests-initially under controlled conditions-of the behavioral response of the target fish to sound are conducted. The purpose of these tests is not only to identify the most effective stimulis, but also to determine its effective range, habituation, and other factors that determine its effectiveness and influence how the sound delivery system is designed and operated. Concurrent with the tests of stimuli, the environment where the behavioral barrier is to be deployed is surveyed to determine its physical features, ambient sound levels, and other factors that might control the distribution of fish, influence fish behavior, or pose special requirements for the sound-stimulus delivery system. Finally, the sound-stimulus delivery system is deployed and operated, the behavioral response of the target fish observed, and the delivery system fine-tuned as necessary. Those who have successfully deployed sound behavioral barriers agree that each step is critical and that eventual success is risked if steps are skipped.

(3)

Panel discussions on how to resolve the critical uncertainties surrounding fish acoustics, how to build a support base for acoustic applications, and improve communication among scientists, industry, and managers

Panel Discussion I: Defining research to support development of acceptable fish-guidance systems.

Three panels were asked to develop a research proposal with a hypothetical budget of $200,000 over two years.

- **First Panel:** Identify effective sound stimulus for endangered salmonids; evaluate the safety of that stimulus morphologically, physiologically, and behaviorally; determine how to generate that stimulus in the field, including modeling of the site-specific acoustic environment; and focus first and foremost on safety throughout the research.

- **Second** Panel: Target salmonids in the juvenile and smolt life-history stages. From the array of guidance systems available (physical barriers, acoustics, lights, bubble fences, etc.), choose a coupling of a behavioral and physical barrier. Obtain cost-sharing from other agencies, and incorporate a product-development aspect in the protocol, inviting vendors to test their systems. Select a location for a model stream other than the Columbia River, with an upstream dam so that flow can be controlled as one of the variables. Choose an alternative site that provides depth as a variable. Introduce a research station at the upper end of the site, and give the fish several miles to migrate down to the structure-basically a barrier dam with a physical fish-guidance sytem built into it-which would allow testing of an acoustic guidance system and a lighting system. Check the health of the fish (clinical parameters) once they have passed the structure for any long-term negative effects such as migratory behavior, etc. First year would be spent developing the sound source and then field-truthing it; the second year would be spent fine-tuning it.

- **Third Panel:** Columbia River salmonids should be targeted. Development of a sound source is not a priority; rather, suitable surrogates could be developed in the short-term to evaluate fish responses to what’s coming out of those sources, and then worry about development later. $200,000 will not develop a sound source in one or two years. Identify stimulus by species, particularly frequency and signal type. Questions of scale

were not resolved by **this** panel. Flume studies were mentioned and selection of a river or stream that's more natural. Need to build a structure that would serve as a pilot plant on a smaller scale.

Panel Discussion II: Issues involved in applying acoustic technologies

The discussion of application of acoustic technologies was far-reaching, with good points made by the panel members. In general, the discussion reinforced points made earlier with special emphasis on the particular experiences of individual panel members. There was general consensus that a systematic approach was more likely to result in a successful application. A ote of realism was also raised from the floor by a representative of a natural resource management agency that emphasized the conservative nature of resource managers and the rather significant barriers to introduction of new technologies, particularly in cases where fish populations were in decline or listed under the Endangered Species Act.

(4)

Workshop wrap-up

Among the priorities that came out of the workshop discussions and presentations were:

- Given the broad spectrum of disciplines represented at the workshop, there is a need to develop a common understanding of the concepts and terminology used to describe the many elements of fish bioacoustics. By using common terminology, we can better extend our knowledge base, link-in with other literature and with basic and applied researchers from many disciplines, and thereby more quickly build a support base for what we need to do.
- Important contributions from basic science relate to (a) effects of sound stimuli on fish, (b) effects of fish morphology and function of the auditory system and lateral line on signal detection, (c) ontogeny of hearing capabilities, (d) the nature of sounds that normally elicit a behavioral response from fish in the wild, (e) problems of habituation to sound, (f) differences between hatchery and wild fish in response to sound, and (g) definition of the sound-detection and response capabilities of fish in the laboratory before a stimulus is tried in the field.
- Interaction and synergy are essential between people doing laboratory-scale experiments and people taking more applied approaches to fish-protection problems. Working together, these investigators must begin looking at large-scale applied questions from the perspective of basic science, and examine the issues raised in large-scale studies from the perspective of the basic biology of fish bioacoustics.
- Acoustic behavioral barriers should initially be viewed not as substitutes for more conventional systems but to supplement or enhance existing systems. Thus, bioacoustic studies and applications are a huge opportunity not only to guide fish using sound, but also to increase understanding of fish behavior which can make other, more conventional behavioral barriers more effective as well. For example, the extremely high-energy hydrodynamics of water passing through screens generate sound fields whose effects are poorly understood but which fall within the general paradigm of guiding fish with sound.
- Acoustic systems must be characterized as completely as possible prior to their

applications, based on the statistical rigor and defensibility of our studies. Also, the current variability in applications that became apparent during the workshop presentations suggests the need for standards of application, not only to link our technologies but also to increase our credibility.

- Given the infancy of bioacoustic applications, we need to build on negative as well as positive results, i.e., exchanging failures as well as successes, and thereby develop our knowledge more quickly.

Note: This workshop was recorded verbatim, transcribed, and then edited in collaboration with the expert panelists. The proceedings are meant not only to provide a detailed record of the presentations and discussions that took place, but also to establish an ongoing state-of-the-art discussion on fish and sound.

Welcome and Introductions

Dr. Thomas Carlson
Pacific Northwest National Laboratory

Good morning, everyone. This is a workshop on fish and sound sponsored by the Bonneville Power Administration, the Portland District of the Army Corps of Engineers, and the Empire. State Electric Energy Research Corporation (ESEERCO), a consortium of northeast utilities. We appreciate their contributions.

I'd like to thank the working group who organized the workshop: Dennis Dunning of the New York Power Authority; John Ferguson, Portland District of the Army Corps of Engineers; John Nestler of the Army Engineer Waterways Experiment Station (WES); John Ploskey with the Waterways Experiment Station Bonneville Field Site; Ed Nunnallee, the National Marine Fisheries Service; Pat Poe of the Bonneville Power Administration; and Art Popper from the University of Maryland.

The workshop is organized into three parts. The first is a tutorial that will cover the physics of underwater sound, the morphology and physiology of the fish hearing system, and elements of the behavioral response of fish to sound. The focus of the tutorial will be to describe in physical terms what constitutes sound, how fish hear sounds, and the within- and between-species differences and variations. Following the tutorial, there will be a series of presentations from people who have applied sound systems to fish-protection problems. Finally, two panels will be convened to discuss some of the uncertainties that hinder application of sound to fish-protection problems. The panels will be open to questions from the floor.

This is the second workshop on fish and sound. The first sound workshop, held in 1992 at Tracy, California, was surprising because it started out with only 8 or 10 people who wanted to get together and discuss issues and quickly grew to include over 200 people. This workshop also included a demonstration of elements of a low-frequency sound system at the Tracy irrigation diversion. The people responsible for that workshop were Charlie Liston of The Bureau of Reclamation and John Nestler of WES. The results of the Tracy workshop were interesting enough to motivate the Bonneville Power Administration to begin a research effort to evaluate if fish-protection systems using sound might aid restoration of Columbia River salmon stocks. This research produced a critical review of previous efforts to use sound for fish protection and resulted in a collaboration between the Pacific Northwest National Laboratory and the Waterways Experiment Station that produced a rationale for a broader research effort, the Acoustic Technologies Program.

The Acoustic Technologies Program has completed its first year of study with several investigations including a baseline study of the morphology of the inner ear of Pacific salmon, tests of the reactance of steelhead to infrasound, and a full-scale test of the guidance effectiveness of a low-frequency sound system at Bonneville Dam on the lower Columbia River. Some preliminary results from these studies will be presented later in the workshop.

Historical Review of the Use of Sound to Modify Fish Behavior

Dr. Thomas Carlson
Pacific Northwest National Laboratory

The primary purpose of this workshop is to transfer information about fish hearing and the use of sound for fish protection to the Columbia River Basin. There seems to be a lot of misinformation, or perhaps a lack of information, about the physical basis of sound, how and what fish hear, and how sound might be used to augment physical barriers or to increase the protection of fish at power plants and other facilities that control water where fish are at risk of injury. Historically, all projects having to do with fish and hearing have begun with the basic question, couched in any number of different ways: Can fish hear? If so, how do they respond to what they hear? I think that almost all fishermen would answer, yes, fish indeed can hear, and that the fact that fish hear really impacts their fishing techniques. But the questions remain: What and how do fish hear, and what behaviors do fish express in response to what they hear? There are many factors, as you'll begin to appreciate from the tutorials today, that influence what fish hear and how they respond to what they hear.

As the tutorials proceed, I believe you'll find that your hearing experience as a human – what sound means to you, how you interpret it, how you understand it – is not a very good guide to understanding how fish hear and how they respond to what they hear. My advice to you is not to extrapolate your knowledge and experience of human hearing to how and what fish might hear.

Investigations of fish hearing began in the early 1800s – probably before that – but the earliest literature begins to appear around 1860. The first attempts to use sound for fish protection didn't begin until the 1950s, facilitated in part by the extensive development of sonar during World War II. Although the physics of underwater sound were well understood and sound projectors of one sort or another and various tools for measuring sound fields were available, these early efforts were marred by poor integration of knowledge of fish hearing, fish behavior, and the physics of underwater sound. During this time, a range of rather strange experiments was conducted, like the one done by the Bureau of Fisheries using a device developed during World War II to detonate underwater mines.

This created a horrendous amount of high-intensity, broadband underwater sound, yet the fish exposed to this noise showed no definite response. Now we believe we understand why this and several other similar experiments failed. However, this experiment set the stage for a host of loosely structured, similar experiments for which the only apparent plan was, "This device makes a lot of underwater noise, let's try it and see if we can get fish to respond."

Behavioral-barrier research reached a peak in the 1970s in terms of both money and effort. As part of a broader program to look at fish-protection technologies, the Electric Power Research Institute (EPRI) looked at a variety of sound stimuli and lights. There were some successes, i.e., some observations where the stimuli seemed to produce avoidance responses. But the basic finding of these studies was that field-scale experiments requiring observation of the behavior of fish are very difficult, and expensive, to perform. Although the results were mixed, nearly everyone involved in the studies concluded that the results in general indicated that fish responded to behavioral stimuli under field conditions. The challenge was to design experiments that could be controlled and that would permit test of hypotheses under conditions where observation and quantification of fish response is very difficult. So while the studies were not generally definitive, they did produce enough results to maintain interest in the potential use of behavioral stimuli as an element of fish-protection systems.

In the late 1970s at a fish-counting station at a lock in North Carolima, a chance observation that herring seemed to avoid high-frequency sound lead the Army Corps of Engineers and the New York Power Authority to further investigate high-frequency sound. The results of these investigations lead to the finding that alosids, in general, showed an avoidance response to ultrasound. The scope of these studies was biological engineering. The reason that this group of fish showed an avoidance response to ultrasound was not determined, but rather that ultrasound could be reliably used to elicit an avoidance response. These studies eventually lead to the use of ultrasound in full-scale fish protection systems. But they also lead fish physiologists to question their understanding of the hearing system of this group of fish.

The first full-scale implementation of sound in a fish-protection system in the U.S. was by the Army Engineers Waterways Experiment Station at Richard B. Russell dam to keep blueback herring out of turbines during pump-back. The second full-scale implementation of ultrasound, by the New York Power Authority at the Fitz Patrick Nuclear Generating Station on the Great Lakes, was developed concurrent with that for the Richard B. Russell dam. Both of these fish-protection systems use a combination of physical and behavioral means to reduce injury to fish.

While there are well documented successes for the use of ultrasound to help protect alosids, for salmon it's been a totally different story. I'm not sure how many studies have looked at salmon hearing and the response of salmon to sound, but it's a long, long list, and it's been a long, long history of failure. A lot of sound has been put in the water with very few observable effects. That isn't much of a surprise, I guess, to the people who know a lot about fish hearing and fish physiology. Compared with alosids, salmonids are considered to be 'hearing-disadvantaged'. You will hear more about that later, but the fact is that they are disadvantaged. The interesting point here is that the information that should have lead to a more promising series of experiments with salmon, while readily available, was not used very well by those conducting the various experiments.

It wasn't until the development and application of infrasound (<20 Hz, or 20 cycles/sec) that laboratory and field studies began to clearly demonstrate startle and avoidance responses by salmonids. In the tutorials you'll learn about the salmonid hearing svstem and gain some insight into why infrasound elicits an avoidance response from these fish.

At this time, the use of sound or behavioral barriers, in general, for fish is very much in its infancy. Effective stimuli have been identified for many species of fish but haven't been developed into effective systems (with the exception of ultrasound for alosids). One of the reasons for this workshop is the need to get a group of interested minds working on the challenge of applying behavioral stimuli to fish protection. One crucial thing that needs to happen, and hopefully we can begin this process during this workshop, is to consolidate and communicate the knowledge base regarding sound and fish, to clarify the present state-of-the-art to help people understand where we are today and how our tools and knowledge may help us get to the point where we have effective fish-protection systems that incorporate behavioral stimuli.

We would like, by the close of the workshop, to have communicated the state-of-the-art in our understanding of the hearing system of fish and the responses of fish to sound along the gradient from startle response through avoidance to guidance, for different fish species. The challenge is to become sophisticated enough in the use of these sounds to cause fish to move from one area to another in a directed way, rather than just startling them and causing an initial reaction that may be undirected. We need to do this in the vertical as well as horizontal dimension; to be able to move fish up and down in the water column as well as laterally across a section of water. We need to be able to work from static conditions, typical of laboratory experiments, to the kinds of flows typically encountered at power production facilities, in dewatering structures, and other water-control facilities. We also need to be able to apply behavioral stimuli across a range of depths from shallow water, on the order of a couple of feet deep, to depths typical of mainstem dams, over 100 feet deep. Finally, we need to know the response to behavioral stimuli of all the life stages of interest, starting with smaller and younger fish, all the way through adult stages. While this is a considerable challenge, the results of the last few years suggest that progress is possible and will most certainly be much more rapid than it has been since the initial experiments in the early 1950s.

That completes my overview of where we are and the scope of what we hopeto accomplish in this workshop. Let’s move on to the tutorials.

Introduction to Fish Bioacoustics

Dr. Arthur N. Popper
U'niversity of Maryland at College Park

This morning we will provide a brief introduction to fish bioacoustics, fish hearing, and sound production. We'll try to keep the talks at a level that will give you some flavor of what we have done over the past years and of the state-of-the-art of fish audition. We are trying to find a common denominator that will help everybody, rather than delving too much into the details of our work.

First, I want to give you an overview, try to define some general terms, and put this morning's tutorials into some context. Tom Carlson's term 'hearing disadvantaged' is very politically correct. However, I'm not sure I agree with the term, because it implies some degradation of the fish's hearing. In reality, the auditory system and lateral-line system of fishes are highly evolved and no doubt serve as the basis for the auditory system in tetrapods and in providing all fish species with the ability to gain a good deal of information about their environments.

Figure 1 gives you some sense of the different organs involved in the talks today. Together, these endorgans are referred to as the octavolateralis system. Perhaps many of you have heard the term 'acousticolateralis system' over the past years (see review by Popper et al. 1992 for an historical overview of this idea). We tend not to use 'acousticolateralis' anymore because it has some evolutionary and developmental implications suggesting that the ear was derived from the lateral line (reviewed by van Bergeijk 1967). The acousticolateralis hypothesis was based upon the idea that the ear and lateral line are innervated by the same cranial nerve, have similar developmental patterns, and have similar functions in hearing. We now know each of these assumptions to be incorrect (see Wever 1974, Popper et al. 1992). For example, the ear is innervated by the eighth cranial nerve, while different cranial nerves (not found in tetrapods) innervate the lateral line. There is also evidence that the two organs develop from different placodes and, as pointed out in the talk by Sheryl Coombs, the ear and lateral line have somewhat different functions.

Thus, in order to avoid the history associated with the term 'acousticolateralis', we use the word 'octavolateralis', meaning endorgans that are innervated by the eighth cranial nerve or by the lateral-line nerves. The lateral line runs along the body and along the head and it has components on the surface or in canals. We also have the ear, which contains a series of receptors in the otolithic organs and the semicircular canals.

The lateral line detects low frequencies of hydrodynamic stimuli of pressure gradients, whereas the ear is more involved in what we call 'hearing' and detecting whole-body accelerations. Both endorgans have in common the same receptor system found in all vertebrates, the sensory hair cell (Figure 2). The sensory hair cell is mechanoreceptive and consists of a cell body and an apical bundle of hairs, or cilia. The ciliary bundle has a single 'true cilium', the kinocilium, and a series of microvilli called 'stereocilia'. The kinocilium has the typical 9+2 tubule pattern found in other cilia.

Figure 3 shows what happens when you bend the ciliary bundle in different directions. Bending towards the kinocilium causes depolarization of the hair cell and an increase in the firing rate of the eighth nerve. That is, the hair cell increases the rate of output to the eighth nerve to the brain. Bending in the opposite direction causes 'hyperpolarization' and a decrease in the response rate of the neuron. This is important for the work that virtually all of us will be talking about, because it indicates that the sensory hair cell is a directionally-sensitive device which responds at a different level for each direction of stimulation.

In the next paper, Mardi Hastings from Ohio State University will give us some background on the sound field and some of the terms and ideas that affect us when we are interested in fish hearing and fish communication. David Mann from the University of Maryland at College Park will talk about why sound is an important means of communication in the aquatic environment. Sheryl Coombs from the Parmly Hearing Institute of Loyola University will talk about the morphology and function of the lateral line. After that, I will talk about the morphology and function of the ear. Then Richard Fay, also from the Parmly Institute, will talk about what fish hear and the kinds of sounds they hear, localization, and things of this sort. And finally, Olav Sand from the University of Oslo will talk about the swimbladder, an important structure involved in sound detection by fishes. He will also describe some of the very important work that's coming out, particularly from Frank Knudsen's lab, on infrasound detection, and relate that to the auditory system.

We will try to talk about fishes from the Columbia River Basin, and especially about salmonids. However, please bear in mind that much of the work on fish hearing has been done with fish not found in the Basin. The goldfish is our 'white rat'. But the principles of sound detection are basically the same no matter where the species are from. At the same time, I want to point out something that my colleague Christopher Platt and I emphasized in a paper we wrote several years ago on *the* fish ear and auditory system, i.e., the word *the* (Platt and Popper 1981). We wanted to emphasize the fact that there is not a single type of fish ear, but, instead, that there is substantial variation in ear structure (and presumably function). As a consequence, extrapolation between species is not always something that can be done easily or correctly.

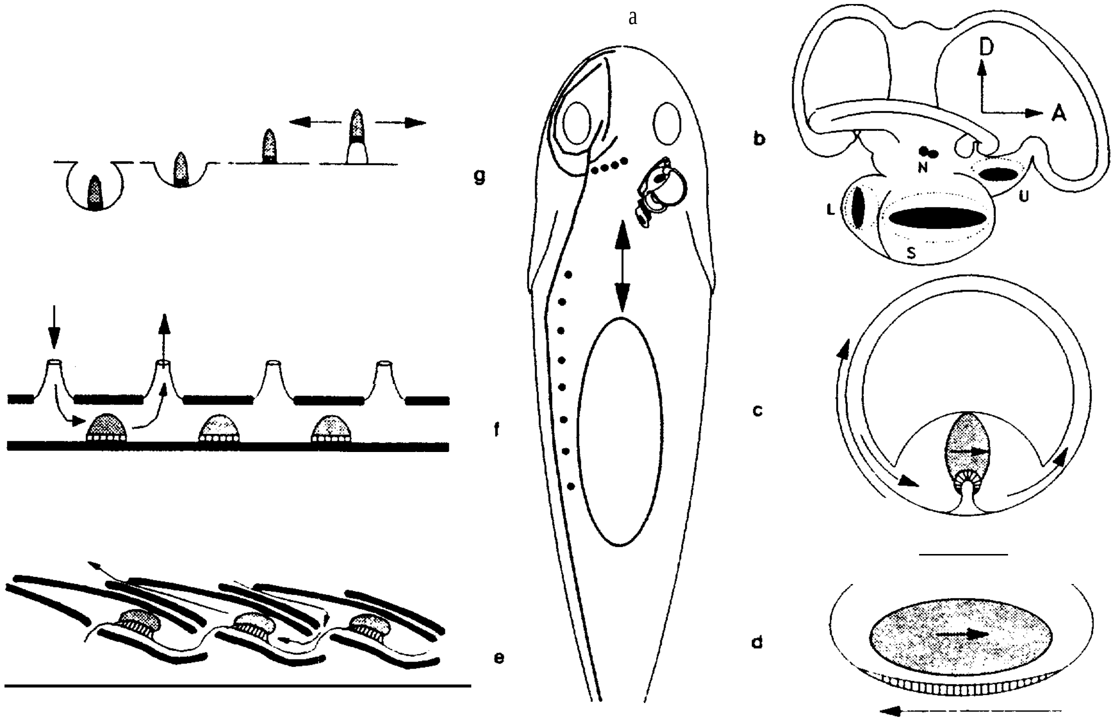

Figure 1

Schematic diagram showing the various components of the octavolateralis svstem. **(a)** Dorsal view of a fish showing the layout of the various endorgans. The lateral-line canals (thick lines) and free neuromasts (small shaded circles) are shown on the left side of the body. The inner ear and its components (semicircular canals and otolithic organs) are shown on the right. The large ellipse is the swimbladder. **(b)** Enlarged view of the right inner ear showing the three otolithic organs (U = utricle, S = saccule, L = lagena) and the macula neglecta (N). The macula neglecta is not found in all species. The sensory epithelia (or maculae) are shown in black, while the dotted outlines represent the otoliths in each otolithic endorgan (A = anterior, D = dorsal). The three semicircular canals. which art' detectors of angular acceleration, are also shown. **(c)** Semicircular canal organ is shown diagrammatically. The sensory cells lie below a gelatinous crista (hatched area). The canal is filled with fluid. When the canal accelerates in one direction (as a result of head motion), the fluid effectively moves in the opposite direction. This results in bending of the cupula, into which project the cilia of the sensory cells. This results in stimulation of the cells (see text). **(d)** Otolith organ. The pouch contains the otolith (hatched) which lies above sensory hair cells. Relative motion of the otolith and the hair cells on the sensory epithelium results in stimulation of the sensory hair cells. **(e)** Lateral-line trunk canal showing the sensory epithelia, or neuromasts, embedded within scales. Arrows show flow paths. **(f)** Lateral-line system on the head of a fish with the neuromasts lying between two pores. Pressure differences at the two pores cause fluid flow in the canal between the pores. **(g)** Variations in surface free neuromasts. All have an overlying cupula, and motion of the water causes cupula bending. Some neuromasts line on the surface of the fish, while others are in pits. (From Platt et al. 1989; used with permission)

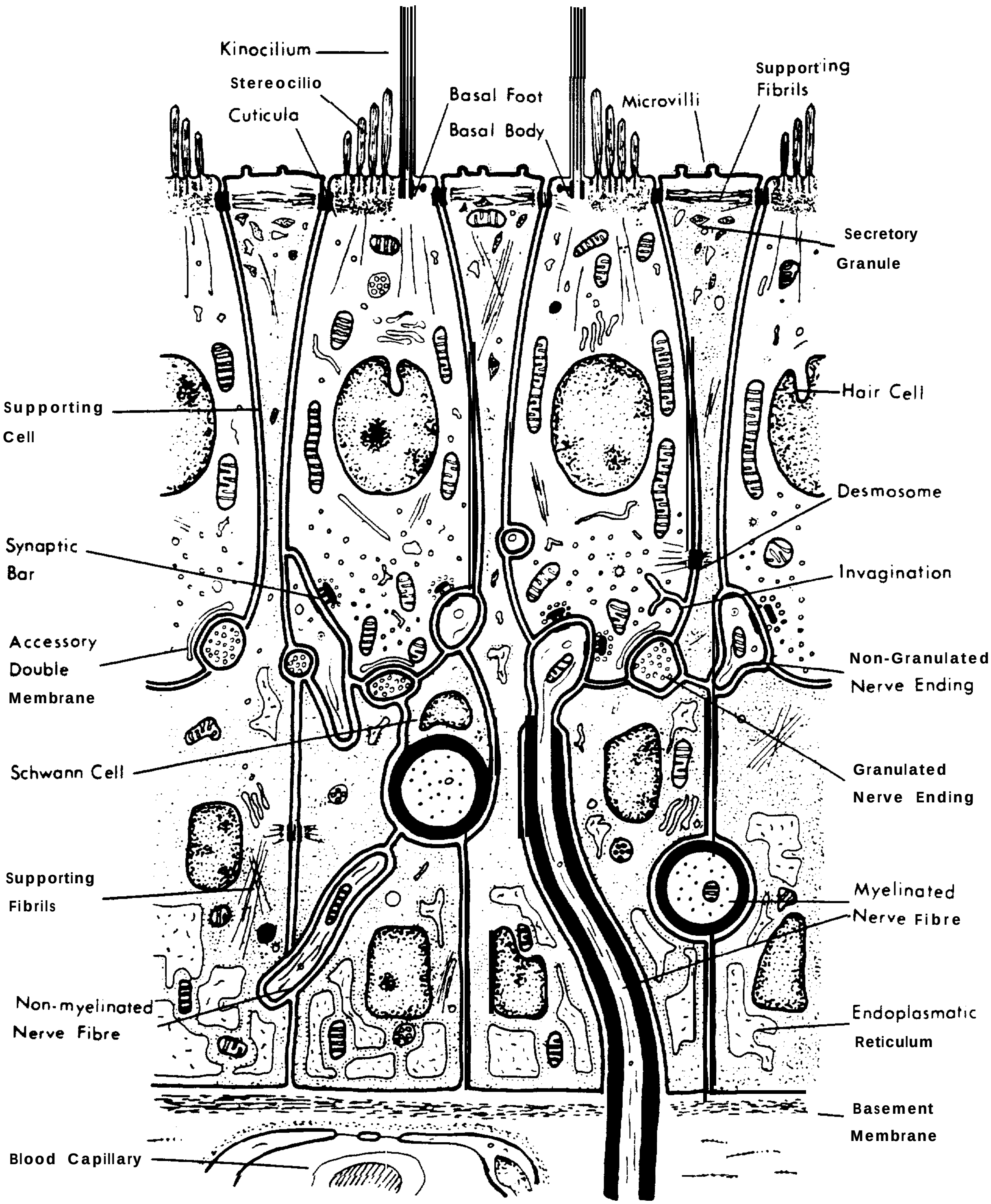

Figure 2

Schematic drawing of sensory hair cells and supporting cells of the lateral line of the burbot, *Lota lota*. The cells in the sensory epithelia of the ears of fishes, and all other vertebrates, are basically similar to those found here. (From Flock 1965; used with permission)

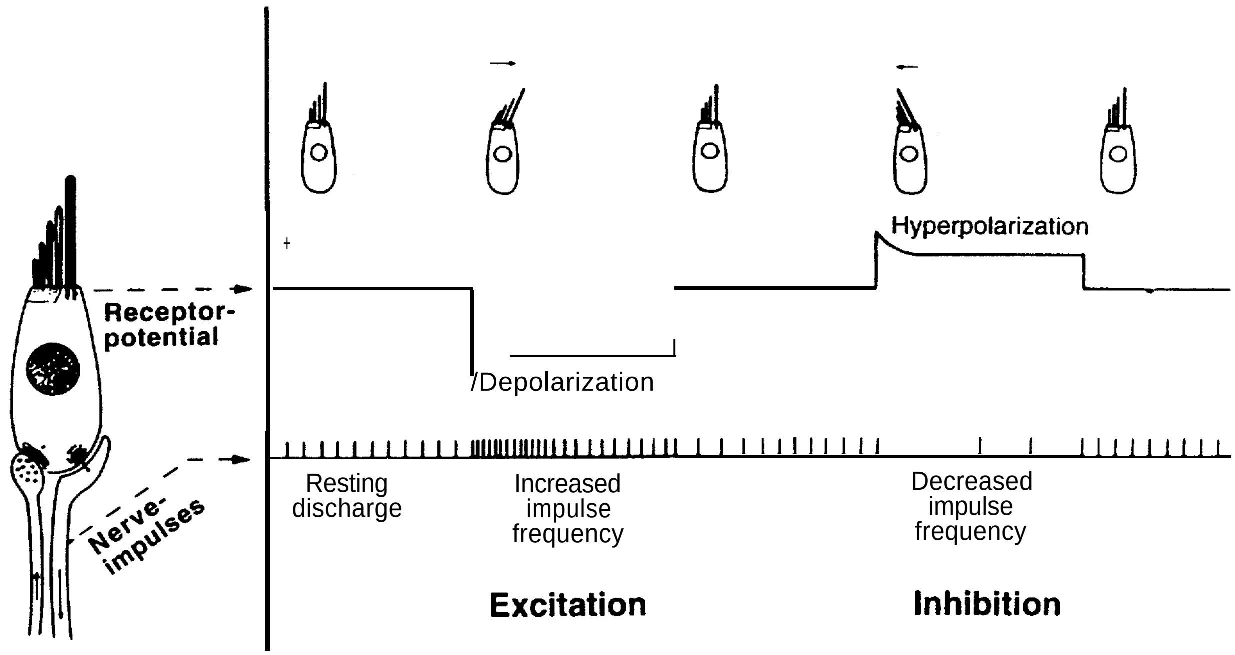

Figure 3

Firing responses of sensory hair cells when the ciliary bundles are bent (sheared) in different directions. Shearing is from the stereocilia towards the kinocilium; the result is a depolarization of the sensory hair cell and excitation of the afferent neurons that innervate the cell. When stimulation is in thr opposite direction, there is an inhibition of the sensory cell and a decrease in the rate of spontaneous activity of the afferent fiber. Shearing (e.g., in and out of the plane of the figure) results in a level of response that is a cosine function of the maximum stimulation of the cell. (From Flock 1964; used with permission)

The Acoustic Environment of Fishes

Dr. Mardi Hastings
Ohio State University

I want to introduce some basics of underwater acoustics, so 1'11 be talking on a fairly fundamental scale. I will talk about the nature of sound and give a qualitative description of sound waves. I'll talk about acoustic quantities and how we quantify sound, some differences between air and water, some models for sound sources and some directional cues that are in sound sources themselves. I am going to talk about the propagation of sound, especially in shallow and moving water. Also I will touch on acoustic field measurements, e.g., how to determine particle velocity when you have a hydrophone that measures only pressure.

I like sound because it's mechanical, and I'm a mechanical engineer. It's longitudinal. Sound will not propagate in a vacuum. It has to have a medium in which to propagate. It can propagate in solids; it can propagate in fluids. Fortunately, in fluids the propagation is quite simple because it can only be longitudinal. The reason for that is that fluids cannot support shear. So in solids you get other types of acoustic waves, but in fluids we have only a longitudinal wave.

Most of us think of sound as a pressure wave, and that's because we can measure pressure. But sound has various descriptors. If the pressure changes locally in a fluid, the temperature and density will also change. In addition, propagation of sound has a vector description, meaning that both magnitude and direction is associated with the acoustic particle velocity, displacement, and acceleration. Whether we talk about sound in terms of vectors or scalars, all these quantities propagate in the fluid at the same sound speed. In this talk, I'll use c to denote the sound speed. We start with fundamental laws to develop wave equations so we can talk about propagation of sound quantitatively. The first is conservation of momentum, or more simply, Newton's second law, "F = ma", for a small volume of fluid:

$$\rho_o \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p \tag{1}$$

where ρ_o is the local mass (i.e., fluid density), $\vec{v}$ is the particle velocity and $\partial\vec{v}/\partial t$ is the derivative with respect to time which gives acceleration, and $-\vec{\nabla}p$ is the negative of the local pressure gradient in the fluid. It's the pressure gradient that actually exerts a force on the fluid and causes it to move. The fluid is accelerated because the pressure exerts a differential force created by its gradient.

If we consider a small volume of fluid and apply the second fundamental law, conservation of mass, then we obtain the equation:

$$-\rho_o \vec{\nabla} \cdot \vec{v} = \frac{\partial \rho}{\partial t} = \frac{1}{c^2}\frac{\partial p}{\partial t} \qquad (2)$$

which simply states that the net flow of mass into the volume must be equal to the time-rate-of-change of density, or the mass that's contained in the volume. To get the relationship between the time-rate-of-change of density and pressure, an equation of state for the fluid is needed. The equation of state will define the sound speed, c. The acoustic pressure perturbation is proportional to the perturbation in density and the constant of proportionality is $1/c^2$. If I take the gradient of both sides of Equation (1) and the derivative with respect to time (t) of both sides of Equation (2), then the left-hand side of both equations will be the same. Then if I add the resulting equations together, I end up with just the right-hand sides which is the wave equation in terms of pressure:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p \qquad (3)$$

Depending on the parameters of interest. the same wave equation can be formulated in terms of density or in terms of particle velocity by combining the appropriate differential forms of Newton's Law (Equation 1) and conservation of mass (Equation 2).

Let's talk about the equation of state. An equation of state that relates pressure (p) and density (ρ) is needed to formulate the wave equation. Then the sound speed is defined as:

$$c = \sqrt{\left[\frac{\partial p}{\partial \rho}\right]_s} = \frac{1}{\sqrt{\rho_o K}} = \sqrt{\frac{E}{\rho_o}} \quad \text{m/s} \qquad (4)$$

where the subscript s indicates that the process occurs at constant entropy. which means in engineering terms that the wave propagation is adiabatic (i.e.. no heat escapes) and also ideal (i.e., a reversible process). The adiabatic assumption is good because conductivity of heat generated in the fluid by passage of the wave occurs much, much slower than propagation of the pressure wave itself. For liquids. the sound speed is $1/\sqrt{\rho_o K}$. where K is the fluid bulk modulus (i.e., fluid compressibility). For linear elastic solids the sound speed is $\sqrt{E/\rho_o}$, where E is Young's modulus of elasticity which characterizes the stiffness of the material.

The sound speed varies quite a bit between air or water. That's one of the reasons why it's difficult to make interpretations when working with perception of sounds by fish. because for fish the sounds will be quite different than they would be for us. For instance, the cues used by fish must be quite different than the (binaural) cues used by humans to localize sound sources because of the difference in sound speed between the two mediums. Table 1 summarizes typical sound speeds for water and biological tissues. At the bottom of the table is a comparison of the speed of sound in water with the speed of sound in air and the speed of light in water. The sound speed is slightly higher in salt water than in fresh water. In either case, however, the sound speed in water closely matches the sound speed in tissues. This makes fish much different than humans in air, because the sound will just go right into their bodies since tissue has about the same sound speed and density as that of the surrounding water. So, a very loud sound might also be doing damage to other organs because most all of the energy associated with the sound wave couples into the fish's body.

Table 1. Sound Speed Values

Medium	Temperature (°C)	Sound Speed (m/s)
fresh water	20	1490
salt water	20	1540
fresh water	35	1500
muscle	35	1566
soft tissue	35	1540

340 sound in air	<	1500 sound in water	<	225,000,000 m/s light in water

One solution to the wave equation that is commonly used to analyze problems is a plane wave. A plane wave can be any function even though many times we assume a wave is sinusoidal (harmonic) or a function composed of a summation of sinusoids. The harmonic solution to the wave equation is:

$$p_{\pm} = f(\omega t \mp kz) \qquad [e.g.,\ p_{+} = P\cos(\omega t - kz)] \qquad (5)$$

where ω is the circular frequency in radians per second (rad/s), t is time, k is the wave number in m^{-1}, and z is the distance along the longitudinal axis of the propagating wave. Thus pressure varies in both time and space. So at a fixed point in space, the pressure disturbance of a passing harmonic sound wave as measured with a hydrophone will be an oscillatory pressure ($p = P\cos(\omega t)$). Likewise. the same pressure oscillation will occur spatially along the longitudinal axis, but it will be changing magnitude and phase with respect to the origin. The wave number (or propagation constant), $k = \omega/c$, defines the change in phase as a function of distance from the source. The ± subscript on p indicates which direction the wave is traveling. A + subscript indicates the wave is propagating in the positive direction from a defined reference point and the argument of the harmonic function would be $(\omega t - kz)$; for a wave propagating in the negative z direction the argument would be $(\omega t + kz)$.

The wavelength (λ) is related to both frequency (f) and sound speed (c). In terms of the wave number, this relationship is:

$$\lambda = \frac{2\pi}{k} \tag{6}$$

Since the frequency in hertz (Hz) is given by $f = \omega/2\pi$, its relationship to wavelength is:

$$f = \frac{c}{\lambda} \tag{7}$$

Thus lower frequencies have longer wavelengths and higher frequencies have shorter wavelengths. If we consider the acoustic spectrum, the terms infrasound and ultrasound are based on our auditory capabilities, not the fish's. The frequency range of the sound we hear is generally defined as 20 Hz to 20 kHz (or 20,000 Hz). Below 20 Hz is infrasound because we can't hear at those frequencies; and above 20 kHz is ultrasound which is at frequencies higher than we can hear.

When we quantify sound, we talk in terms of decibels (dB's); a decibel is a power ratio. When we talk about sound power (P), we talk in terms of intensity or the power flow per unit area. Sound intensity ($\vec{I}$) is given by the pressure multiplied by particle velocity ($p\vec{v}$). For a plane wave propagating in one direction, the relationship between pressure and particle velocity is $v = \frac{p}{\rho_o c}$ where $\rho_o c$ is the characteristic impedance of the fluid (and the vector notation has been dropped because we are considering propagation only along the longitudinal axis). Substituting this relationship in the formula for sound intensity gives $I = \frac{p^2}{\rho_o c}$. Since power is proportional to the square of the sound pressure, then sound pressure level in decibels is given by 20 times the log of a pressure ratio. The pressure ratio is the sound pressure divided by a reference pressure. The reference pressure for water is 1 μPascal (μPa) and the reference pressure for air is 20 μPa. Thus sound pressure levels in air and water will not be the same for the same acoustic pressure because they have a different reference pressure. Table 2 summarizes the decibel relationships for sound pressure, power and intensity. One of the reasons that we use a decibel (dB) scale is because the pressure range from our threshold of hearing (or even a fish's threshold of hearing) up to our threshold of pain covers many orders of magnitude.

Table 2. Quantifying Sound

Quantity	Symbol	**Reference Level**	**Formula (dB)**
Sound pressure level	SPL	1 μPa	$SPL = 20\log\left(\frac{p}{1\,\mu Pa}\right)$
Sound power level	PWL	10^{-12} w	$PWL = 10\log\left(\frac{P}{10^{-12}\,W}\right)$
Sound intensity (power per unit area)	IL	10^{-12} W/m^2	$IL = 10\log\left(\frac{I}{10^{-12}\,W/m^2}\right)$

Plane waves are, planes of constant pressure that propagate longitudinally. A plane wave doesn't have to be a harmonic function. It can be any function of time as long as it repeats itself in space:

$$p(\vec{R},t) = f\left(t - \frac{\vec{n}\cdot\vec{R}}{c}\right) \tag{8}$$

$$\vec{v}(\vec{R},t) = \frac{\vec{n}}{\rho_o c}\, p(\vec{R},t) \tag{9}$$

wherefdenotes any function, $\vec{R}$ a spatial vector in Cartesian coordinates, $\vec{n}$ the unit vector perpendicular to the planes of constant pressure and pointing in the longitudinal direction, $\vec{n}\cdot\vec{R}$ the direction of propagation, and $\rho_o c \approx 15 \times 10^6\ Pa - s/m$ *the* characteristic impedance for water.

Figure 1 illustrates the propagation of a plane wave. The time it takes for the wave to begin to repeat itself in space is the period, *T*. The product of the sound speed with the period (cT) gives the distance between repetitions of the pressure shape. Again, the particle velocity that's associated with the plane wave is just the pressure divided by the characteristic impedance, $\rho_o c$. Mismatches between this characteristic impedance and the acoustic impedance of other objects and surfaces cause sound to be reflected or scattered at the interface. For waves propagating in a single direction, we often drop the vector notation and refer to these quantities as scalars, i.e., $p = \rho_o c v$ or $v = p/\rho_o c$.

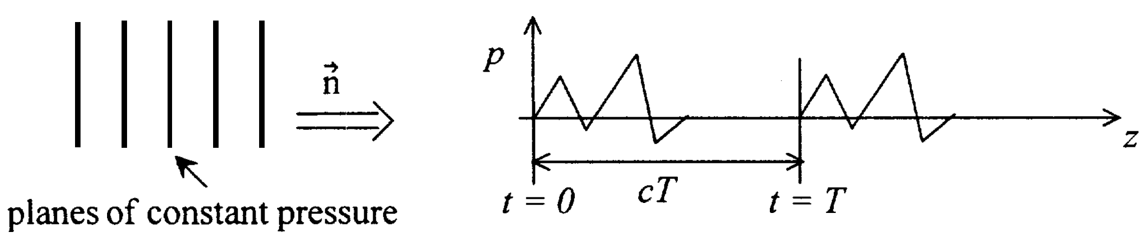

Figure 1. A plane wave propagates longitudinally with period T (seconds).

So what causes a wave to propagate? Figure 2 illustrates a control volume (indicated by dotted lines) analysis showing that the acoustic pressure and particle velocity must be in phase for the wave to propagate in the positive direction. The negative gradient on the right side of the pressure peak causes the fluid to accelerate in the positive-x direction because pressure is higher on the left side of the control volume than on the right side. Acceleration in the positive direction increases (↑) the particle velocity which causes a net increase of fluid flow into the control volume. A net increase of fluid in the control volume creates an increase (↑) in pressure as well. On the left side of the pressure peak, the pressure gradient is positive. This decelerates the fluid resulting in a decrease (↓) in particle velocity. As the amount of fluid in each control volume decreases, the pressure also decreases (↓). Thus the wave propagates to the right when the pressure and particle velocity are in phase. For the wave to propagate in the opposite (i.e., negative) direction, the pressure and particle velocity must be 180" out-of-phase as shown in Figure 3. The relationship between pressure and particle velocity could provide cues that fish use to localize sound sources.

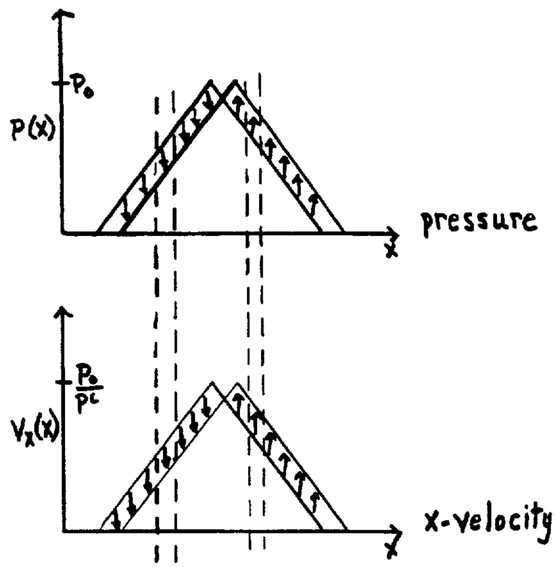

Figure 2. A plane wave propagates in the positive direction (away from its source) when the acoustic pressure and particle velocity are in phase.

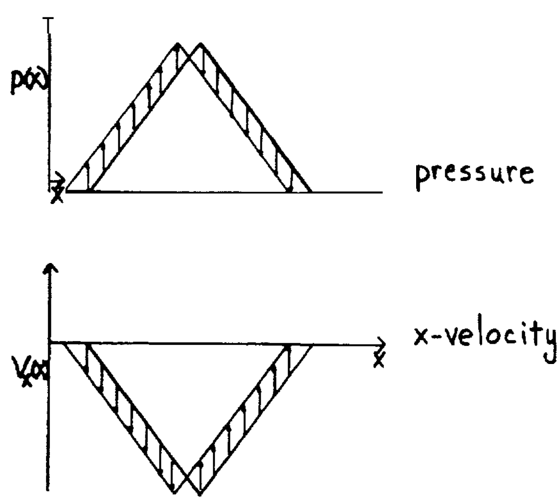

Figure 3. A plane wave propagates in the negative direction (towards its source) when the acoustic pressure and particle velocity are out of phase.

Spherical waves propagate radially outward such that the pressure is a function of radius from the center of the source. They form spherical surfaces of constant pressure. Figure 4 illustrates propagation of a spherical wave. Because energy is conserved, the pressure decreases as the distance (radius r) from the source increases. This relationship is given by:

$$p(r,t) = \frac{f(t - r/c)}{r} \tag{10}$$

The decrease in pressure (intensity) with increasing radius is called spherical spreading.

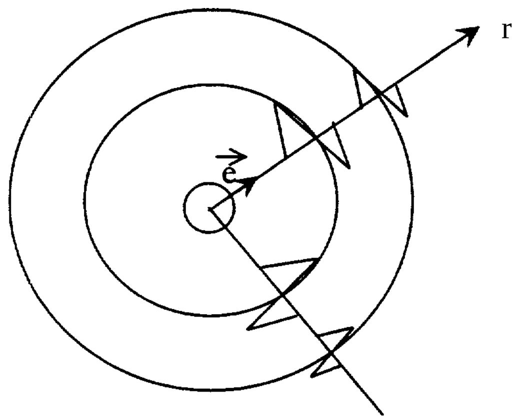

Figure 4. A spherically symmetric wave propagates radially outward from a source in all directions; the pressure decreases with $1/r$.

The acoustic particle velocity generated by a spherical source has two parts, one that propagates due to the compressibility of the fluid and the other that is more of a bulk flow near the source:

$$\vec{v}(r,t) = \left[\frac{p(r,t)}{\rho_o c} + \frac{\int_0^t p(r,\xi) d\xi}{\rho_o r} \right] \vec{e}_r \tag{11}$$

where $\vec{e}_r$ is the unit vector in the radial direction (i.e., the direction of wave propagation). Far away from the source ($r >> 1$) in the "far-field," the relationship between pressure and particle velocity is the same as that for a plane wave, $v = p/\rho_o c$. Closer to the source in what is called the "nearfield," the second term (hydrodynamic flow) in the Equation (11) is important. The far-field is defined by the following conditions:

- $p = \rho_o c v$;
- $r >> c \times [\textit{characteristic time}] = \lambda$ *for harmonic waves*;
- and $r >>$ *source dimension (including images).*

One thing to be concerned about is the distance from the source relative to a wavelength (λ). At 50 Hz, λ = 30 m in water and usually measurements are made only one meter away from the source to characterize it. At a frequency of 50 Hz, one meter will be in the nearfield of the source.

One simple model for a source is a monopole, which is a sphere that's changing volume. A monopole is a sphere that breathes: when the sphere expands outward, an increase in pressure (compression) occurs and when it moves inward a decrease in pressure causes a rarefaction in the surrounding fluid. This variation in volume creates a spherical acoustic wave in an unbounded medium. The pressure and particle velocity generated by a monopole are given by:

$$p = \frac{-\rho_o \omega a^2}{r} U_o \sin(\omega t - kr) \tag{12}$$

and

$$v = \frac{a^2}{r^2} U_o \cos \omega t - \frac{\omega a^2}{cr} U_o \sin(\omega t - kr) \tag{13}$$

where a is the radius of the sphere and U_o is the linear velocity of the wall. The first term on the right-hand side of Equation (13) is the nearfield term which falls off with $1/r^2$, and the second term is the farfield term which falls off with the radius just as pressure does.

Many biological sources, though, are modeled by what is called a dipole. A dipole source is a sphere that moves back and forth along an axis through its center as illustrated in Figure 5. When the sphere pushes against the fluid, the pressure increases, and when the sphere moves back it decreases. The effect on the other side of the sphere is just the opposite, i.e. pressure changes are 180" out of phase with those on the other side; consequently, the pressure field resembles a figure eight. The particle motion associated with this pressure field will follow the pressure gradient. So the flow field forms a figure eight that is perpendicular to the axis along which the sphere oscillates. Thus the particle velocity and pressure field are "dipolar' and that's why this type of source is called a dipole. A dipole produces sound by accelerating the fluid which results in generation of a pressure gradient. The pressure and particle velocity are given by:

$$p = \frac{-\rho_o \omega a^3}{2r^2} U_1 \cos\theta \sin \omega t - \frac{\rho_o \omega^2 a^3}{2cr} U_1 \cos\theta \cos(\omega t - kr) \tag{14}$$

and

$$v = \frac{a^3}{r^3} U_1 \cos\theta \cos \omega t + \frac{a^3}{2r^3} U_1 \sin\theta \cos \omega t - \frac{\omega^2 a^3}{2c^2 r} U_1 \cos\theta \cos(\omega t - kr) \tag{15}$$

where U_l is the linear velocity of the sphere and θ is the angle with respect to the axis of oscillation. In this case, the pressure has a near-field term that falls off with $1/r^2$ and the particle velocity has two near-field terms that fall off with $1/r^3$. In the farfield, both the pressure and the particle velocity are proportional to l/r.

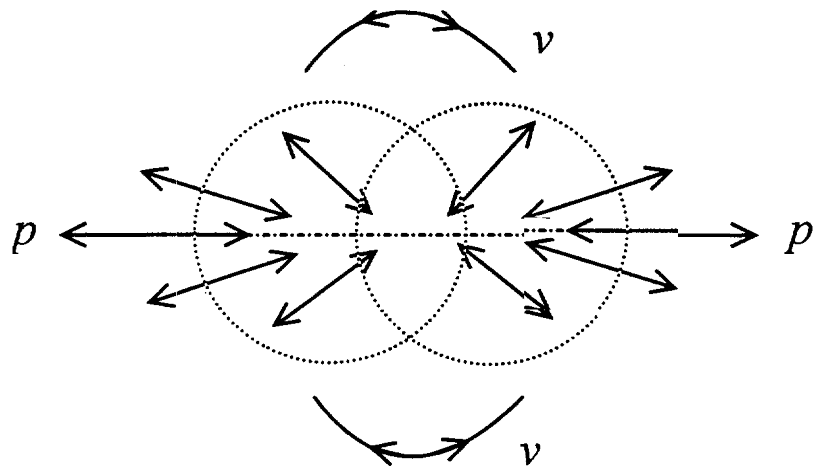

Figure 5. The pressure (p) and particle velocity (v) fields generated by a dipole source.

Other types of sources include air guns which create a large explosive air bubble in the water. The air bubble expands as soon as it is released from the gun, and when it can't support the fluid pressure, it collapses. This is a low frequency source that generates an acoustic wave by the rapid expansion and collapse of an air bubble. A very commonly used source is an electrodynamic or piezoelectric piston transducer. In the nearfield, on the axis perpendicular to the face of the piston, the pressure field oscillates creating nulls and peaks which are twice the farfield pressure. Thus care must be taken when using this type of sound projector in its nearfield.

Underwater propagation is affected by absorption, surface and bottom reflections. refraction (due to the sound speed profile and objects), and water depth. Attenuation due to absorption of sound increases with frequency as shown in Figure 6. Of course. sound doesn't attenuate nearly as bad as light in water, which makes it a good means for underwater communication.

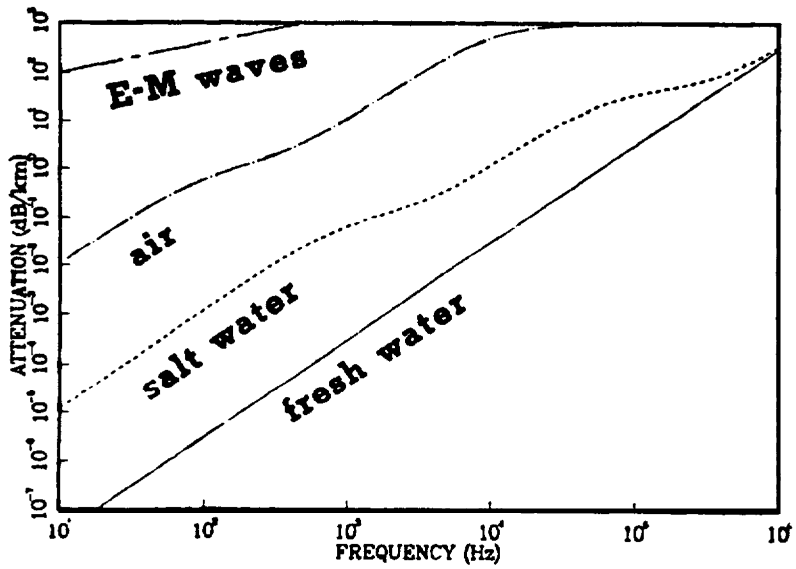

Figure 6. Attenuation of sound in water is much less than attenuation of sound in air or attenuation of electromagnetic waves (light) in water.

Although the water surface is an excellent reflector of sound, the reflected wave is upside down and backwards relative to the incident wave as illustrated in Figure 7 where the reflection coefficient is $R = -1$. It is very difficult to make measurements near the surface because the acoustic pressure is extremely small since the surface reflected sound tends to cancel the direct sound. The bottoms of bodies of water are usually poor reflectors ($\boldsymbol{R} < 0.5$).

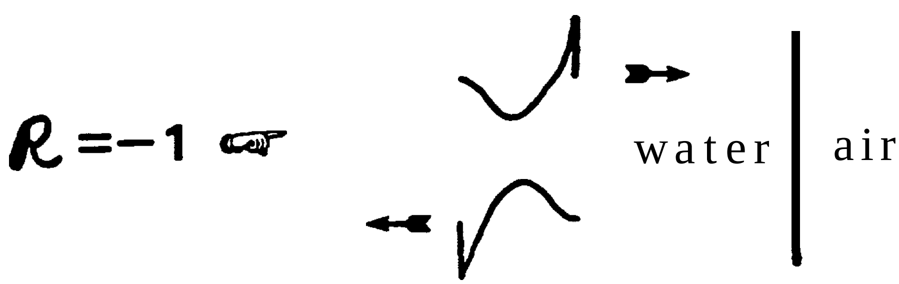

Figure 7. Reflection of sound at the water surface creates a wave traveling in the opposite direction that is 180” out-of-phase with the incident wave.

In addition to specular reflection, the surface and bottom (and other objects) may “scatter” sound in other directions owing to surface roughness. Scattered sound pressure is the pressure that would not be there if the scattering object or surface was not present. The swim bladders in fish scatter sound as do local concentrations of gas bubbles and other objects.

Refraction of sound is bending of the wave due to a change in sound speed at an interface or a sound speed gradient, usually created by gradual changes in fluid temperature. Sound speed increases with temperature. So if the water is hotter on the surface, as it would be during the summer, sound waves will bend downward as they approach the surface. The waves will always bend toward the lower sound speed. Refraction can cause channeling of sounds, regions of good reception (caustics), or regions with no reception (shadow zones).

Propagation of sound in shallow water is a diffkult problem. Sound waves will have repeated interaction with both the surface and bottom. The wave equation must be solved as a boundary value problem. The solution to the wave equation for this case consists of a finite sum of normal modes. Each mode is a standing wave in the vertical direction that propagates in the horizontal direction with its own frequency-dependent speed. Each mode has a cutoff frequency below which it cannot propagate. No sound can propagate at frequencies below the cutoff frequency (f_c) for the first mode:

$$f_c = \frac{c_w \; 4h}{\sqrt{1 - c_w^2 \; c_s^2}} \tag{16}$$

where c_w is the sound speed in water, h the water depth and c_s the sound speed of the bottom. Figure 8 shows the cutoff frequency for different types of bottom materials. For example, with a fine sand bottom the cutoff frequency is about 1000 Hz for a water depth of one meter. This means sound at frequencies below 1000 Hz will not propagate.

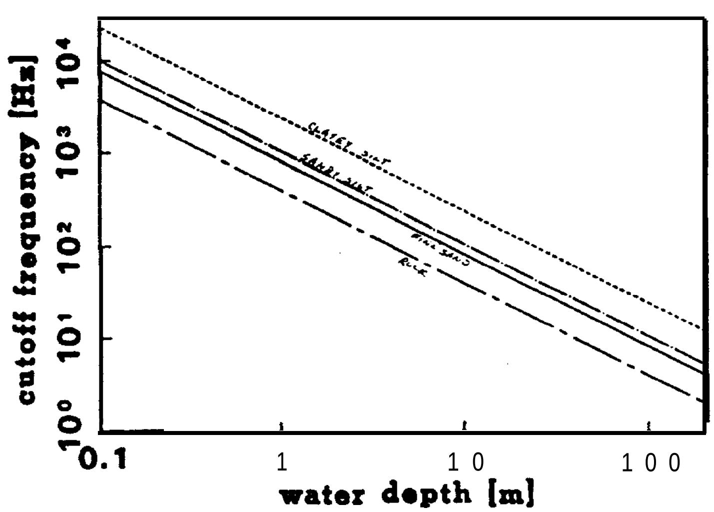

Figure 8. Cutoff frequencies for propagation of sound for different bottom materials; at frequencies below cutoff, sound will not propagate in shallow water.

No commercially available sensors exist to measure acoustic particle velocity except at very high frequencies and in the nearfield of a source at very low frequencies because neutrally buoyant accelerometers are sensitive enough to detect particle acceleration under those conditions. A good estimate of the particle velocity amplitude ($|v|$) can be obtained at nearly all frequencies, however, by measuring the local pressure gradient ($\Delta p/\Delta x$) with a hydrophone and applying conservation of momentum (Newton's second law or Euler's equation):

$$\frac{\Delta p}{\Delta x} = j\omega\rho_o|v| \tag{17}$$

where $j = \sqrt{-1}$. This technique has been used successfully in several laboratories.

Behavioral Uses of Sound by Fish

Dr. David Mann
University of Maryland

Introduction If you were to take a boat out into a river, lake, or ocean and drop a hydrophone into the water, you would be unlikely to hear anything except, perhaps, some noise. Based on this experience, you might conclude that fish don't produce sounds. But if you watch and listen for a long time, you might hear occasional sounds produced by fishes.

I want to talk about the kinds of sounds that fish make and the behaviors associated with those sounds. Many fish make sounds for some communicative purpose, such as aggression and courtship. They also produce non-intentional sounds, like a fish rubbing against gravel on the bottom or sounds associated with feeding. I will focus on those fishes of the Columbia River Basin that are known to produce sounds. thus, this will not be a comprehensive review of fish sound production. I will bring in examples of sound production by other fishes, where examples of local fishes are lacking.

I will show a number of oscillograms and sonograms of sounds produced by fishes to give you a feeling for the kinds of sounds that are produced. An oscillogram is a representation of the acoustic pressure signal that is picked up by the hydrophone. Sounds can also be represented on sonograrns, which are on the same time-scale as oscillograms but which show the frequency of the sound over time.

Aggression/Defense Figure 1 shows the sound made by the river bullhead (a kind of sculpin) in an aggressive interaction. The sonogram is shown above the oscillogram. The sound is pulsed and low frequency (<1000 Hz). If you watch these fish, most of the time they aren't doing anything; but if they are involved in aggressive interactions, they *may* be making sounds.

Courtship and spawning Here is an example of a courtship sound produced by many species of sunfishes (Figure 2). The oscillogram is shown above and the sonogram is below. Individual pulses in the sounds are labeled A, B, C, and D. The sonogram shows that these are low-frequency sounds, <1000 Hz.

Figure 3 shows a sonogram of the spawning sound made by haddock, a gadoid fish. This is not a pulsed sound, but a tonal sound that lasts for over 30 seconds, with a dominant frequency of -50 Hz. There are also harmonics associated with this sound at -100 Hz and 150 Hz. In general, you don't tend to find the sort of frequency modulation in fish sounds that you hear with bird singing. Fish sounds are either tonal or pulsed. The burbot, a freshwater gadoid, is found in the Columbia River Basin. Sounds have not been recorded from the burbot, but it likely produces sounds because it has sonic muscles on its swimbladder.

Swimming and feeding sounds These sounds are probably incidental and without communicative purpose. Fish that are schooling or escaping from a predator will often make sound. Many fish have pharyngeal jaws in their skulls which they use to grind up food, which results in sound production during feeding. Other fishes may be able to hear these sounds, but **this** has never been tested.

Figure 4 shows feeding sounds made by Pacific herring, which are broadband clicks that extend from very low to very high frequencies. Here's the swimming sound made by a school of these fish (Figure 4B). Again, it's a broadband sound ranging from 100 to 500 Hz. Basically, it sounds like a rush of noise associated with swimming.

Figure 5 shows feeding sounds made by rainbow trout. These are clicks made by the fish chewing on food (Figure 5b). The fish also produced a series of clicks after eating. It's very difficult to tell from the papers on salmonid sound production what kinds of sounds the fish are making with which behavior. This sound in Figure 5c is typical of a fish sound, and provides evidence that salmonids are capable of making sounds. Unfortunately, we really don't know that much about sound production dur.ing aggression and reproduction in salmonids.

Sound characteristics and mechanisms of production Fishes that produce tonal sounds, such as haddock, have muscles on their swimbladders which they contract to product sound with a dominant frequency at the rate of muscle contraction. The haddock I showed you was **contracting** these muscles at 50 Hz on the swimbladder. Sounds produced by muscles on the swimbladder tend to be the loudest sounds made by fishes and the easiest to hear. If you're swimming in the water with them, you can hear them. Unfortunately, there are few measurements of sound-pressure levels of fish sounds. Toadfish produce the loudest-known fish sounds at 140 dB//1μPa.

Fishes with swimbladder muscles can make pulsed as well as tonal sounds. They just contract in bursts, sot it sounds more like a grunt. But other fishes make pulsed sounds with stridulation. They either grind their pharyngeal jaws together or, in the case of catfishes, they have a pectoral spine that they can stridulate. Pulsed sounds are broadband and tend to range in frequency from 100 to 1000 Hz.

Timing of sound production One reason that you may not be able to detect sounds produced by fishes is that most fishes produce sounds during limited periods of the day or year. Most of the time, fishes are not producing sounds.

Figure 6 is from a paper on sound production in cod. They had cod in tanks and were watching them during spawning. Figure 6 shows the time-series of the rate of sound production. You can see that from 9 a.m. until about midnight, the level of sound production is very low. It starts increasing at dusk until the fish spawn, then it decreases. So if you looked for these fish in the middle of the day to see if they were making sound, you wouldn't hear anything. You would have to be there at dusk, and you would have to be there when the fish were spawning.

Figure 7 is a time-series from my work with damselfish, and shows the level of variation you can see in sound-production behavior. There are two curves plotted here. The calling rate is the solid line, and the light level is the dotted line which shows you day or night. As you can see, these fish generally are calling during the day and not so much at night. Sound-production peaks on the days of spawning (indicated by an 'S'). The other thing you notice are the peaks in sound production at dawn and dusk. This pattern of sound production is very similar to the dawn course in birds, and is found in other fishes.

Range of communication Vibrational signals, which are very low-frequency signals that Sheryl Coombs will talk about, act within a few body lengths of the fish. The distance over which the fish sounds I've shown you will be used in communication depends on their intensity, characteristics of the water body in which the fish lives, and background noise. There are few data on the propagation of fish sounds, but many of these fishes live in shallow water that degrades the quality of low-frequency signals as they propagate. Background noise probably limits the range of communication for these fish. Dick Fay will talk later about masking. Taken together, existing data on the loudness of fish sounds and natural levels of background noise suggest that most fish sounds are used over distances less than tens of meters. The point is that fish are not like whales which communicate over thousands of kilometers.

Columbia River Basin fishes known to make sounds I compiled a list of papers that show species in the Columbia River Basin that make sounds and the type or description of the sounds they make (Table 1). Usually when a fish sound is described, the associated behavior is not described. So there are salmon that make feeding or clicking or grinding sounds. Channel catfish make stridulation sounds. Sunfish and mottled sculpins make sounds. I also compiled a list of what I think are potential sound producers (Table 2). We haven't made any recordings of these fishes, but they belong to families with known sound producers. In the clupeid family, I showed Pacific herring sounds. They also supposedly produce chirp and whistle-type sounds, although that recording was made in the open ocean and could be from some other source. Shad in the Columbia River Basin certainly could make sounds. There are cyprinids, such as the flat-finned shiner and gudgeon, that are known to make sounds associated with aggression and courtship. And there are a number of cyprinids in the Columbia River Basin that could also presumably make sounds. Cod and haddock make aggressive, courtship, and defense sounds. The burbot has sonic muscles on its swimbladder, so it probably makes sounds like the haddock. Then there are these families for which we have absolutely no idea, such as suckers, pikes, smelts, striped bass, and perches.

Environmental sounds There are a number of other sound sources besides these fish, such as wind, waves, rain, biological sounds like insects in the water, and, of course, human-generated sounds. Orientation is **one** of the ways that fish could use these sounds. While salmon have been known to use chemical cues while returning to streams, it's possible that in long-distance orientation, when returning from very far out, they use the noise produced by waves and such for orientation. Sound provides a good directional cue oer very long distances. However, there are no data on whether or not they actually do this.

Another thing the fish could be doing is using sound to get an acoustic scene of their environment. The water / air interface is a very reflective surface which can produce echos in sounds. The ambient noise and the reflections could tell the fish where it is in the water, how deep the water is, and that sort of thing. Just like we can get an idea of the size of this room by the sound of my voice. If we were in a closet, my voice would sound very different to you. And these fish could presumably use sound produced by their prey to localize them. Hawkins and Johnstone (1978) proposed that Atlantic salmon could listen for prey. Although there are no data to confirm this, there is good evidence of vibration detection by the sculpin, which Sheryl Coombs will talk about.

Effects of sounds/noise on sonic fish behavior One concern about using sounds to try to deter fish is that there may be side-effects on both the target and non-target species. Fish that use sound for communication could be affected by increased masking of background noise or by damage to their hearing. This could be especially relevant for those species that use sounds during reproduction. Unfortunately, there are no data on the effects of sounds on sonic fish behavior.

Summary In summary, many fish make sounds associated with aggression, defense, courtship, and spawning, although most of the time they are probably not making sounds. These sounds are typically pulsed or tonal and low-frequency (50-1000 Hz). They are likely used for communication over short distances, on the order of less than tens of meters. We don't know that much about the role of ambient sounds in normal fish behavior. And we know nothing about the effects of noise on the behavior of sonic fishes.

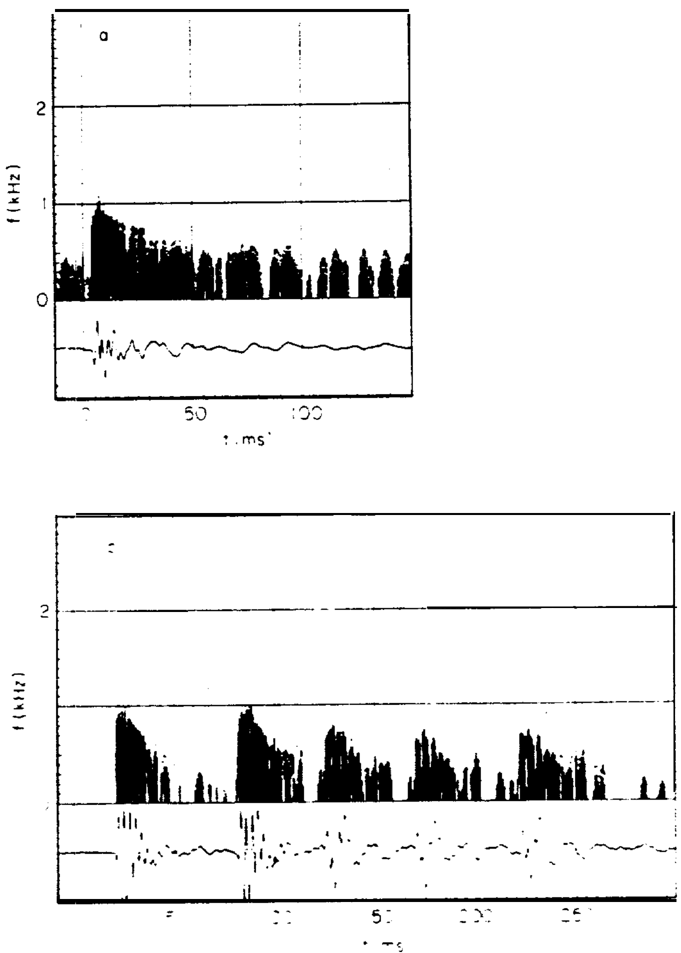

Figure 1
Sound production by the river bullhead, *Cottus gobio* L. (Cottidae, Teleostei). (Ladich 1989)

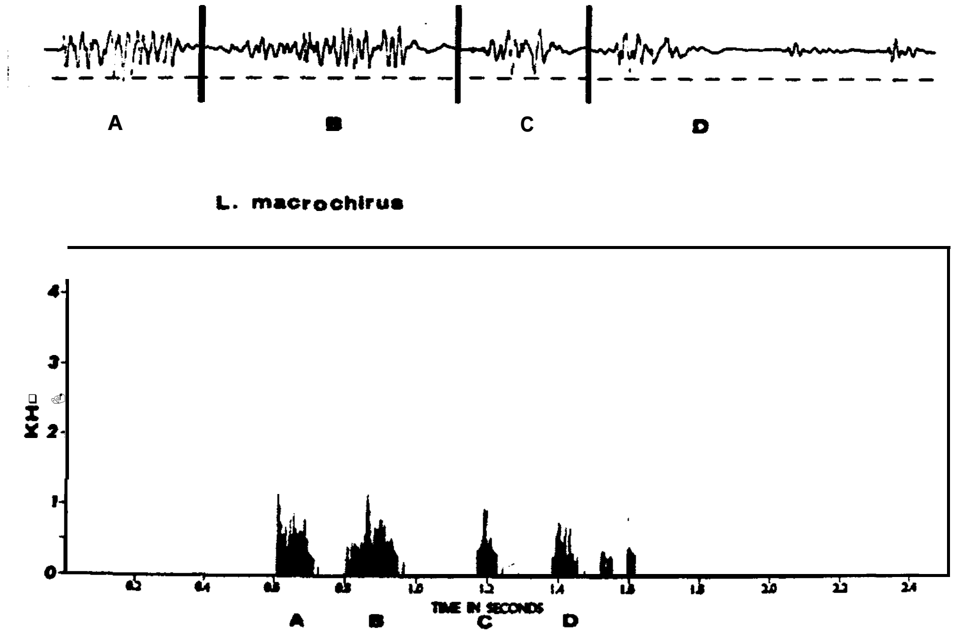

Figure 2
Sound production during courtship in six species of sunfish (Centrarchidae). (Gerald 1971)

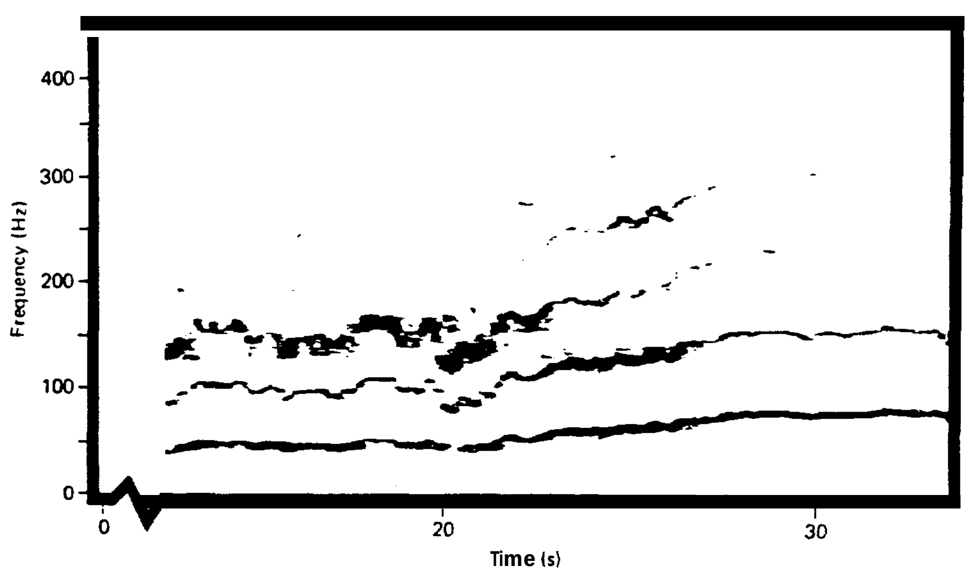

Figure 3
The calls of gadoid fish (Hawkins & Rasmussen 1978).

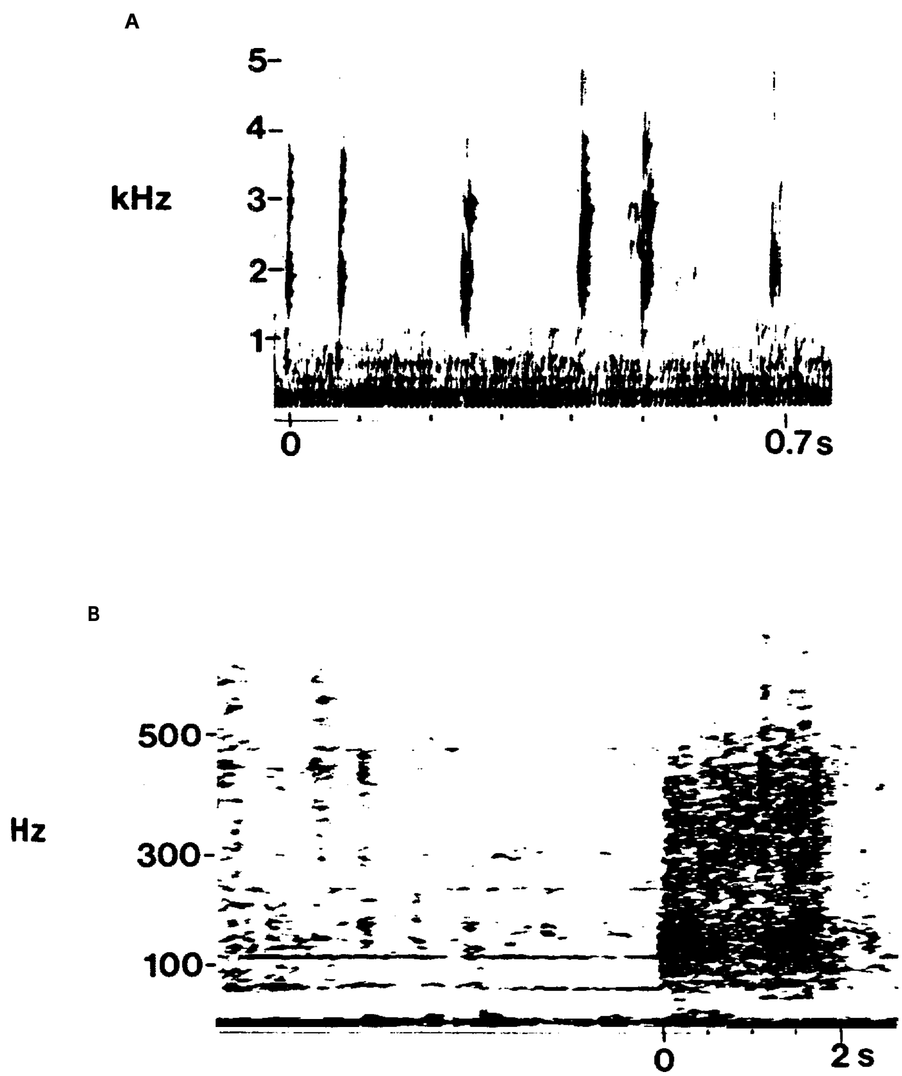

Figure 4
Responses of Pacific herring, *Clupea harengus pallasi*, to some underwater sounds.
(Schwarz & Greer 1984)

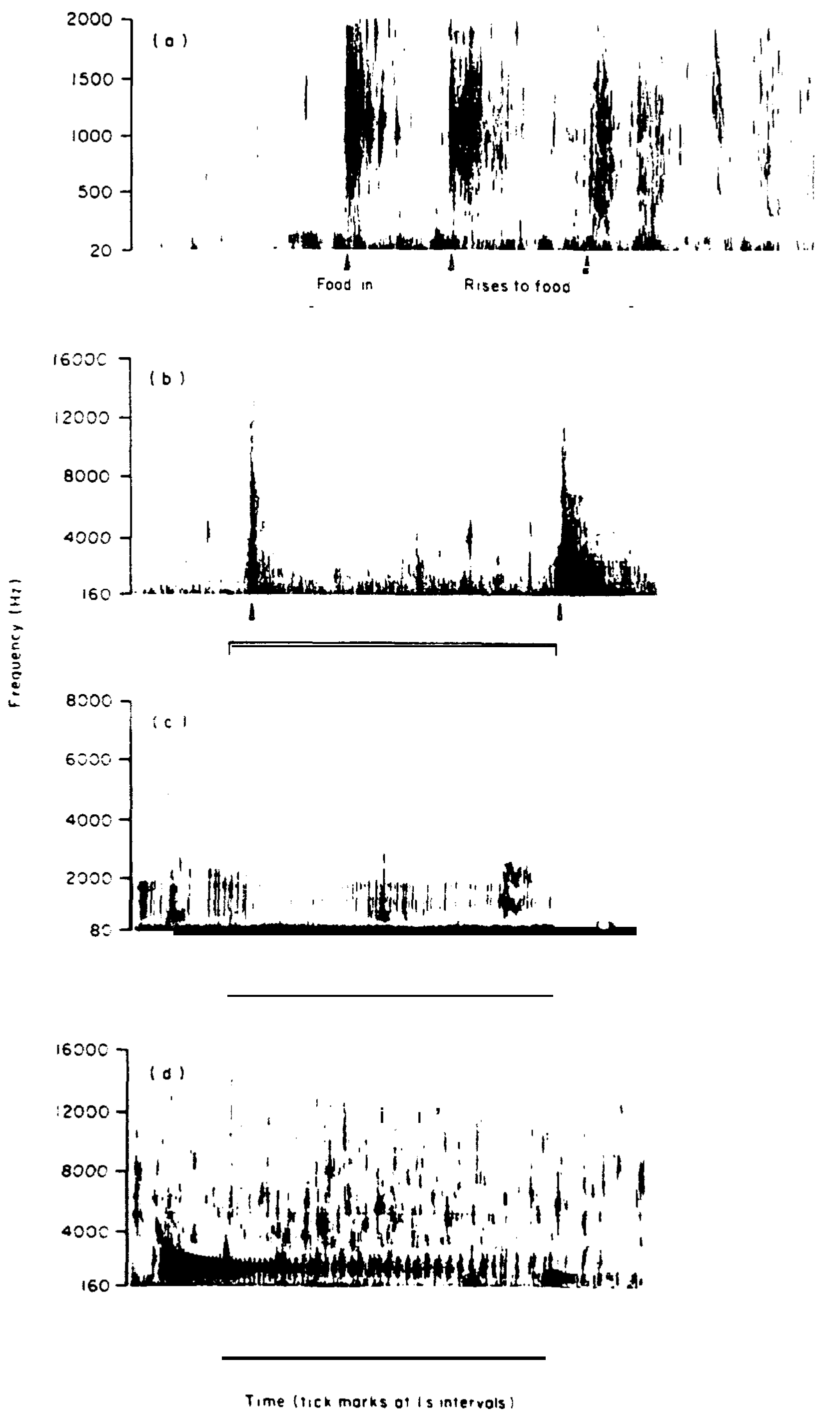

Figure 5
Feeding sounds of rainbow trout, *Salmo gairdneri* Richardson.
(Phillips 1989)

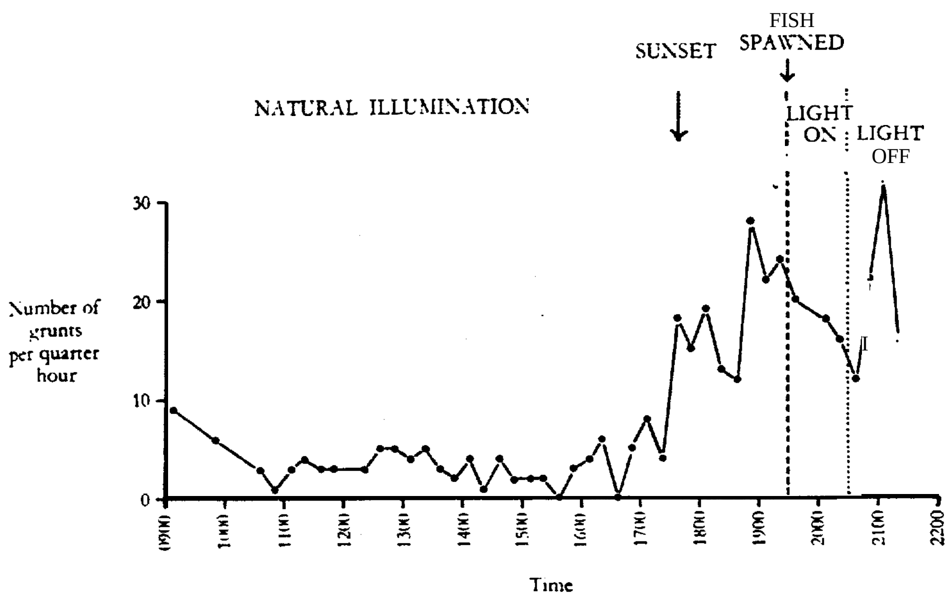

Figure 6
Frequency of sounds produced by a group of 13 cod, 48-73 cm long,
on the first spawning day, March 4, 1957.
(Brawn 1961)

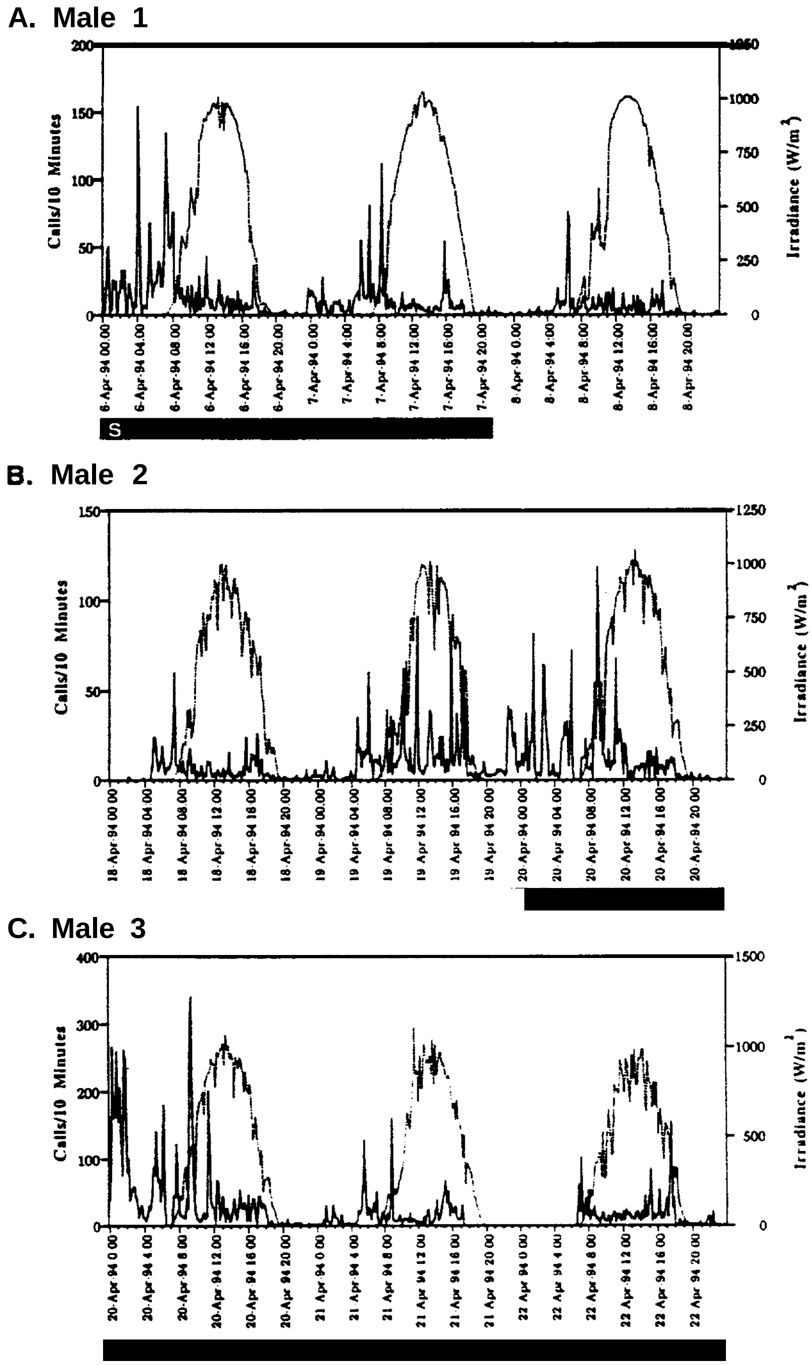

Figure 7

Rate of sound production in calls/l0 min (solid line) plotted with irradiance (dotted line) for three individuals. Bpxes below dates indicate days eggs were present in a male's nest. Day of spawning is indicated by an 'S' in the box. (Mann & Lobe1 1995)

Columbia R. Basin Fishes Known to Make Sounds

Family	Species	Common Name	Sound
Salmonidae	*Salmo gairdneri*	Rainbow trout	Feeding
	Oncorhynchus nerka	Sockeye salmon	"clicking, grinding"
Ictaluridae	*Ictalurus punctatus*	Channel catfish	Stridulation
Centrarchidae	*Lepomis macrochirus*	Bluegill sunfish	Courtship
	Lepomis cyanellus	Green sunfish	Courtship
Cottidae	*Cottus bairdi*	Mottled sculpin	Reproduction (vibrations)

Table 1
Columbia River Basin fishes known to make sounds.

POTENTIAL SOUND PRODUCERS

Families containing sonic fish found in Columbia River Basin

Family	Sonic Species	Sound	Columbia River Basin
Clupeidae	*Clupea harengus* Pacific Herring	chirps *whistles*	*Alosa sapidissima* American shad
Cyprinidae	*Notropis anulostanus* Satfin shiner	aggression courtship	Goldfish, shiner, dace, squawfish
	Gobio gobio gudgeon	aggression, defense	
Gadidae	*Gadus callarius* cod	aggression, courtship	*Lota lota* Burbot (sonic muscles!)
	Melanogrammus aeglefinus haddock	defense courtship, spawning	

Columbia River Basin Fish Families for which there are No Data

Catastomidae	Suckers
Esocidae	Pikes
Osmeridae	Smelts
Percichthyidae	Striped bass
Percidae	Perches

Table 2
Potential sound producers in the Columbia River Basin.

Question & Answer Session

DR. NESTLER: You identify many environmental sounds that you might characterize as background, and you also say there is no evidence that fish respond to those sounds. I think maybe the key question is, could they respond to those sounds? Are those sounds within their sensory range?

DR. MANN: Yes. Certainly they can detect reflections from the surface of the water. Dick Fay, I don't know if you can talk about that, but fish do have the capability of detecting those sounds.

DR. CARLSON: I will address some of that, as well, John.

MR. HENDERSON: The definition for nearfield, farfield – that's mechanical. And I have noticed that the biologists use a different definition in responding to the nearfield and farfield, although I haven't been able to figure out which definition they use, or if they are consistent among themselves. Have you any comment on that?

DR. HASTINGS: I'm not sure I know what you mean by 'mechanical'. Just relationship between particle velocity and pressure?

MR. HENDERSON: Yes.

DR. HASTINGS: What I was showing was that you have to be away from the source much longer than a wavelength to be in the farfield. What that physically boils down to is that if I'm within a wavelength of the source, I get these hydrodynamic flow fields, and the fish have different detection mechanisms for that type of field. And the other part is that, once I get past the hydrodynamic field (of course, there's this gray area, a transition), then what's truly called 'sound' or 'acoustic signal' propagates, not because the fluid is flowing like a bulk flow, but because it's compressible. And ways to look at that are by measuring local pressure gradients to estimate the particle velocity and then compare that to what would be the plane-wave value. And if the particle velocity is equal to the pressure over the acoustic impedance of the medium, then you are in the farfield. Otherwise, it will be much, much larger than that. Does that help?

MR. HENDERSON: I have heard this a number of times from biologists, trying to determine where is the farfield and nearfield where particle motion is concerned.

DR. HASTINGS: And I guess it's fuzzy, it depends on each individual situation. It depends on the size of your source, on the wave length, and on local velocities.

DR. FAY: I think that you always have to worry about particle velocities. I think fish hearing has evolved to detect particle motion. That's essentially what it does. And so I think that is more important than trying to say whether or not we're in a nearfield or farfield, because even a particle-motion detector, as Mardi pointed out, will detect sound in the farfield because there is particle motion there. And so the real question is, what is the receiver, what is it responding to? And then if you're doing an experiment, let's measure that. That's where I think the issues really come out. I think we should always figure that you're probably in the nearfield, unless you are talking about whales communicating overlarge distances.

DR. COOMBS: Sound detection in the farfield is enhanced when you have an air-compressible structure like the swimbladder. In that case, you've got a pressure-detecting mechanism for transmitting pressure pulses into displacement, which then will impinge upon the inner ear. So basically, the unspecialized auditory system without air-compressible cavities and the lateral-line system are confined predominately to near-field. And thus pressure-transducing structures help to extend the working range of the auditory system.

MR. LOEFFELMAN: Some of your guesses about sounds and freshwater fish are correct. I have auditioned many of those fish, and they do make sounds. So we can talk about that, including salmonids.

DR. NESTLER: There is something that has bothered me for many years, and it is that those naturally-occurring fish sounds are actually quite complicated. We describe them using the physics of monopoles and dipoles, but I am curious as to how much information loss there might be in interpreting those complicated natural sounds using the physics of monopoles and dipoles.

DR. HASTINGS: All I can say is that I agree, and if you have multiple sound sources or you have a complicated source, what you really need to use is a multipole expansion. If you noticed, when I went from monopole to dipole I had more terms for a harmonic signal. You can have octopoles, you can have quadrapoles. But many times, when we are working on laboratory-controlled experiments, it's much simpler to have a simple sound source so you can understand the relationship between pressure and particle velocities, say. That's why you see many references to monopoles and dipoles, especially dipoles. It is true, though, in the nearfield, that a dipole source is a pretty good model for a lot of fish motion. For farfield, maybe, maybe not.

I'd like to make one other comment about the pressure/particle velocity in the nearfield/ farfield. Fish don't have to be specialists to detect particle velocity of acoustic wave. What makes the fish so remarkable is that it can detect very, very small motions. So even if it's in the farfield and it doesn't have a specialized connection with its swimbladder, it's still going to detect motion. One recent experiment that Art Popper and 1 have done, and 1 think he has some of that data to show later for a traveling plane wave. Essentially, we can create a farfield source in my lab that will induce hair cell damage under certain conditions. Hair cell damage in oscars was induced when particle motion was the highest. And so, just because the fish doesn't have a pressure connection to the inner ear doesn't mean that the fish can't detect true sound. I think all that energy going right into their body helps fish do that. There's no membrane translation, like we must have, to get the particle motion directly into the inner ear.

MR. MENEZES: Basically two comments. The nearfield/farfield – that's been a point of discussion, and a lot of times you get into this gray area. If you are a transducer manufacturer, you tend to use sonar systems, in the conventional sense. You usually go out of your way to make sure you are in the farfield, in terms of much more well behaved. To me, the issues of getting into nearfield are that you are dealing with all the irregularities, and the micro-scopics of the situation are very important. What you can have here and what you can have 3 inches away might be fundamentally different as a function of time.

Regarding the other issue that John Nestler alluded to, yes, the monopole / dipole model is a fairly basic characterization of the sounds that are produced biologically. In fact, in some sonar systems we're trying to do biological rejections, because there are some fundamental differences between sounds produced biologically and those that we tend to produce electronically for use in sonar applications. We look at things like stable cycle counts and pulse-length variability, ping-to-ping basis, you know. The stable cycle count is very important to look at. I don't know to what degree those things are important or to what degree we have to take that fidelity and apply that to the sounds you put in the water. I guess we will have to work out the details on that. But you are right, it is a fairly simple characterization of a complex sound.

DR. NESTLER: What 1 am really driving at is that we're mammals, and we are using light as cues. And if we were to measure photons and wavelengths of the light environment that we're in, and to analyze that using some simple optical model, we would totally miss the point of being mammals and how we really acquire information, visually, from our environment. I view acoustics in the same light. Probably there are all sorts of analytical shortcuts that fish are using to acquire information out of that complex acoustical background, just like we're using shortcuts and processing tricks to acquire information using vision. What I'm really afraid of is that by applying simple models to hearing, we are making the same mistake for fish as we might be making in interpreting our own world, using light as a cue.

DR. HASTINGS: I would like to follow-up on that, because there have been papers presented and published that make the direct analogy with our vision. When we see things, we're looking at reflected and scattered light. And one of the things that's always puzzled me and a lot of other people when we start working in this field with fish is that if you look at marine fish in the ocean, they hear the best where the noise is the highest. Their *ears* are tuned to the ambient noise. And so the line of thought is that it's the same analogy as with light; their eyes are essentially their ears underwater, and they detect reflected and scattered signals off objects. And that's this 'acoustic seeing' type of thing.

And there have been experiments done by Pete Rogers at Georgia Tech showing that a goldfish could detect the presence of a hollow sphere in a sound field, whether the sphere was there or not, through a scattered signal. And so you're right, you have to be very careful. The fact is that, whatever your source, the object is not out of the noise, so to speak; it's modulating the noise and that may be what the fish are detecting.

Structure and function of the fish lateral-line system with special emphasis on Columbia River fishes

Dr. Sheryl Coombs
Loyola University of Chicago

What I'd like to do today is give you a very general talk about the anatomy, biomechanics, physiology and behavioral function of the lateral-line system in fish, with an emphasis on what is known about Columbia River fishes, at least to the extent possible. I will elaborate on some recent research we've done in our lab on the role of lateral-line excitation patterns in guiding fish to vibratory sources. But I'll also borrow from the work of many others to try to give you as complete a picture as I can about this somewhat enigmatic sensory system. Since I have a lot of material to cover, I won't be able to acknowledge all the investigators in the field who have contributed to this picture. I apologize for that, but I have prepared a list of references that cover all the material I will present today (see bibliography).*

The lateral-line system is basically a collection of small mechanoreceptive patches distributed on the head and body of all fishes and many larval and postmetamorphic amphibians. It can best be thought of as a system that detects small water currents very close to the animal, generally within one or two body lengths. Probably the best way to describe this system is a sense of 'touch at a distance' (Dijkgraaf 1962[1]). The lateral-line system has been shown to be important in a number of different behaviors. One such behavior is schooling (Partridge & Pitcher 1980, Partridge 1982, Pitcher et al. 1976[2]). Partridge (1982[2]) describes two different evasive schooling formations used by dwarf herring to avoid predation by barracuda.

Another behavior that's been studied in the blind cavefish is what I will call 'active hydrodynamic imaging of the environment' (Campenhausen et al. 1981[2]; Hassan 1986, 1989[2]). It's active in the sense that fish are actively producing a flow field by swimming or gliding and then using their lateral-line system to detect perturbations in the flow field due to the presence of stationary obstacles. This ability is quite acute, and it's been shown that blind cavefish detect millimeter differences in spacings between vertically-oriented rods (Hassan 1986[2]). This same general principal applies to the detection of stationary objects in any kind of flow field, e.g., rocks in a stream. Only in this case, we might think of it as a form of passive rather than active hydrodynamic imaging. This is probably what brook trout do when they maintain more or less stationary positions behind submerged obstacles in streams. Trout are able to do this in total darkness; and if you cut the lateral-line nerve innervating the trunk on one side of the fish, it now keeps the object on its intact side (Sutterlin & Waddy 1975[7]). It's been

*Note: To make the bibliography more user-friendly, it has been divided into seven sections. The number in brackets following each text citation refers the reader to the bibliographic section where it is found. [1] General references (chapters, review papers, entire books); [2] specific references related to lateral-line mediated behaviors and sensory capabilities; [3] specific papers describing the anatomy, development, and function of the lateral-line systsem; [4] specific papers describing the role of pressure-gradient (i.e., flow) patterns and lateral-line excitation patterns in guiding fish behavior; [5] book chapters that compare and contrast lateral-line and auditory function in fish; and a comprehensive listing of lateral-line references on [6] clupeid and [7] salmonid fishes – two commercially important groups of fishes impacted heavily by water-power facilities.

suggested that fish such as salmon and trout actually exploit the oncoming vortices from these obstacles to boost their swimming efficiency during their arduous upstream voyages. In fact, lateral-line monitoring of vortex formation by the swimming fish itself has been proposed as a key feature that may enable many fish to swim as efficiently and skillfully as they do.

The lateral-line system also plays a role in intraspecific communication during the courtship behavior of salmon (Satou et al. 1987, 1991, 1994[7]). Synchronous spawning between the sexes in the landlocked red salmon is achieved through a series of behaviors involving body vibrations between males and females in close proximity to each other. When the lateral-line system is pharmacologically blocked, both spawning approaches and spawning acts are significantly reduced.

Finally, the lateral-line system is important in feeding behavior. There's a whole body of literature on the role of the lateral line in surface-feeding by fish like the top minnow (e.g., Bleckmann et al. 1989131). In our lab, however, we've been studying how Lake Michigan mottled sculpin use their lateral-line system in detecting subsurface water motion created by the small vertebrate and invertebrate prey on which they feed. There are at least seven species of freshwater sculpin, including the riverine mottled sculpin, inhabiting the Columbia River drainage. My current understanding is that they are both prey and predators of some of the more economically important species, like salmon and trout. Mottled sculpin are swimbladder-less benthic fish that normally feed at night, when vision is severely restricted. In fact, if you blind them in the lab, they will respond to the vibrations of a nearby chemically-inert object, such as a small sphere, with an initial orientation towards the source followed by a stepwise approach to the source. When the source is less than a few centimeters away, they strike at the source. If you pharmacologically or mechanically block the lateral-line system, the orientation and subsequent approach and strike behavior completely disappear, indicating that the lateral-line system is extremely important in helping these fish locate nearby vibratory sources. I will come back to this behavior at the end of this talk when I discuss the role of lateral-line excitation patterns in guiding sculpin to vibratory sources.

I hope by now I've given you some appreciation of the variety of behaviors for which the lateral-line system is likely to be important. Now I'd like to switch gears and tell you something about the anatomy of the system and what we understand about its biomechanical and physiological functioning. As Art Popper has already introduced, the sensory cells in the lateral-line system are called 'hair cells', and these are the same kind of sensory cells found in all vertebrate ears. Hair cells are innervated by *afferent* fibers that carry information from the hair cell to the brain and by *efferent* fibers that relay information from the brain to the hair cell. Bending the hairs in the direction of the eccentrically-placed kinocilium leads to an increase in the firing rate of the afferent fiber, whereas bending the hairs in the opposite direction leads to a decrease in the firing rate (Flock 1967[3]).

Hair cells in the lateral-line system exist in discrete patches called 'neuromasts' which are spatially distributed over the body of the fish. Free or superficial neuromasts, as indicated in Figure 1 by the small dots, are found on the skin surface usually in several specific locations on the head and on the trunk of fish. Neuromasts can also be found in fluid-filled canals just below the skin surface. Canals in teleost fishes are typically located above and below the eye, across the top of the head, along the preopercle and mandible, and along the trunk (Figure 1).

Canals are either embedded in bone (typically on the head) or are housed in individual tubes embedded in each trunk scale. Scales are typically arranged in shingle-like fashion to form a continuous canal along the trunk, as they do in the trout (see Kroese & Schellart 1992[7]). In both cases, there are usually pores (sometimes extended by tubules enclosed in flesh, scale, or bone) that lead into the canal proper such that there is one neuromast between every two pores (or tubules) (Figure 2). These tubule/pore openings provide the main route by which water motions outside the canal cause fluid motions inside the canal, leading to the stimulation of neuromast hair cells.

On the dorsal surface of each neuromast is a gelatinous cupula which helps to transmit the motions of the surrounding fluid to the ciliary (hair) bundles, which project up into the cupula. In canal neuromasts, there are two oppositely-oriented populations of hair cells, one that responds best to flow in one direction along the canal, and the other to flow in the opposite direction. Each of these is innervated by separate nerve fibers. This means that there are separate channels for encoding the direction of water movement inside the canal, and this will become important later on when we talk about how lateral-line excitation patterns contain information about source locations.

To summarize, we have two subclasses of endorgans: superficial and canal neuromasts (Figure 2). In general, superficial neuromasts tend to be smaller and have fewer hair cells, but the cupulae of both are thought to be driven primarily by viscous forces. That is, water flowing past the cupula causes it to move by virtue of friction coupling with the cupula surface, and the cupula response is proportional to the velocity of water flowing past it. Because flow velocity inside the canal is proportional to the net acceleration between the fish and the surrounding water, canal neuromast responses are more proportional to acceleration (Denton & Gray 1983 [4], Kalmijn 1988[1]). Another way of thinking about fluid flow inside the canal is that it is proportional to the pressure gradient across the two canal pores (Coombs et al. 1996[4]). No matter how you think about the effective stimulus, the bottom line is that there has to be relative movement between the fish and the surrounding water before either superficial or canal neuromasts will be stimulated, and this usually occurs when the stimulus is very close to the fish -within one or two body lengths.

Table 1 lists some of the anatomical dimensions along which the lateral-line system can vary between species (Coombs et al. 1988[3]). Obviously, this list raises the question of whether anatomically different systems have different biomechanics and thus function in fundamentally different ways. The answer to that question is probably both 'yes' and 'no'. Let me illustrate the 'yes' part of this answer with examples from the last two categories of this list that are applicable to fishes in the Columbia River Basin.

The first example is taken from the unusual octavolateralis system of clupeid fish, like the American shad (Blaxter & Denton 1976, Blaxter et al. 1981a[6]). These animals are atypical in a number of ways, including the presence of a highly branched tubule system leading into head lateral-line canals and the absence of a trunk canal. But they are unique, as far as we know, among teleosts in having all head canals radiate from a central enlarged sinus called the 'lateral recess'. Positioned in the wall of the skull at the back of the lateral recess is a compliant membrane in contact with inner-ear fluids, as shown schematically in this slide. With this kind of mechanical linkage, a change in pressure in the air-filled swimbladder-bulla complex ultimately causes excitation of lateral-line canal neuromasts on the head (Denton & Blaxter 1976 [6]). This highly unusual configuration means that both the ear and lateral line will respond to pressure fluctuations over time and that the lateral-line system can be stimulated in the absence of a pressure gradient along the canal. The significance of this arrangement to lateral-line function has yet to be fully understood, but it has been linked to the extraordinary schooling abilities of many of these fish, for example, the predator-avoidance formations that you saw earlier for dwarf herring (Partridge 1982[2], Blaxter et al. 1981c, Blaxter & Hoss 1981[6]).

As a second but fundamental example, I'd like to say something about the functional distinction between superficial and canal neuromasts. Keep in mind that the relative abundance and distribution of superficial vs. canal neuromasts may differ between species. For example, many charciform and cypriniform otophysan fish have thousands of superficial neuromasts distributed all over the body of the fish, whereas by comparison there are very few on the mottled sculpin. In fact, there is this notion in the literature, although not examined in any systematic way, that abundance of superficial neuromasts is correlated with stagnant-water habitats (e.g., Dijkgraaf 1962[1]). So what might these superficial neuromasts be doing for these fish?

The answer lies in Figure 3, which compares the responsiveness of canal neuromast fibers to superficial neuromast fibers when the lateral-line system is being stimulated by a small bead vibrating at different frequencies but at constant maximum-flow velocities. As you can see, the responsiveness of both fiber types falls off quickly after -50 Hz. This simply reminds you what is true for all lateral-line systems, that is, they are low-frequency systems. It turns out that this particular example is taken from an Antarctic fish, so the high-frequency cut-off is atypically low (Coombs & Montgomery 1994[3]). For temperate-water fishes like our mottled sculpin or trout, the cut-off might not occur until >100 Hz or so.

But if we just focus on what's happening <50 Hz, canal fiber functions reveal that low-frequency responses are reduced relative to high-frequency responses and also relative to low-frequency responses of superficial neuromast fibers. Based on this comparison, one might argue that the primary function of superficial neuromasts is to detect very low-frequency signals (say <20–30 Hz or so) and that of canal neuromasts is to detect higher-frequency signals.

This brings us to the question of what are the low- and high-frequency signals and noises that fish encounter in their natural environment. Unfortunately, there's very little information on this topic, but here's a brief summary of what we know (Table 2). Based on this kind of information, one might speculate that superficial neuromasts would be best at detecting low-frequency signals, such as those generated by the fish's own steady swimming movements, but that the usefulness of superficial neuromasts in detecting exogenous signal sources, such as swimming prey, would be compromised by low-frequency noise whenever the fish moves or finds itself in moving water. In this context, the primary function of the canal would be to improve the signal-to-noise ratio at higher frequencies, perhaps for detecting wakes behind swimming prey or submerged obstacles.

We've now characterized the response functions from fibers innervating head-canal neuromasts in six species of Antarctic fish for which we expected to find functional specializations (Montgomery et al. 1994[3]). I think these results show quite clearly that reduction in low-frequency responses relative to higher frequencies is a general feature of canals in all of these species. The remarkable thing about this particular example is that this low-frequency reduction persists, despite rather dramatic differences in the overall size, shape, and compliance of canal walls in several of these species.

This brings me to an important point I want to make about anatomical variation within the lateral-line system. That is, you can't and shouldn't automatically assume that all morphological variation translates into functional variation that's significant to the animal. This is a perfect example of where there can be a lot of morphological slop without affecting essential function, and where the answer to our original question may be 'no'.

The final point I want to make about anatomical variation is that much of it can be predicted by, and in fact is constrained by, how the system develops. At hatching, all neuromasts are superficial and only some of these, depending on their location, become enclosed in canals as the fish grows. This developmental sequence consists of an invagination of the neuromast into the skin, the enclosure of the neuromast into a canal segment, and finally the joining of two segments to form a continuous canal interrupted by a pore (see Janssen et al. 1987[3]). Basically, this means that in the early life history of the fish, the lateral-line system consists of only superficial neuromasts and will not have the advantages afforded by canals. In chum salmon, for example, we know that canal formation is not complete until the 6-7 cm fingerling stage (Disler 1971 [7]).

Now that you have some basic information about the overall anatomy and function of the lateral-line system, I'd like to tell you about some work in progress in our lab that addresses the question of how mottled sculpin localize underwater sound sources. This work capitalizes on the naturally-occurring orienting and feeding behavior of these fish and on a wonderful computer program written by Mardi Hastings and some of her students at Ohio State University which uses the flow-field equations for a dipole source to model the excitation pattern to the lateral-line system. Let me show you what I mean by this.

At the top of Figure 4, I've depicted the pressure and flow lines about a dipole source, which is just a small sphere vibrating back and forth at 50 cycles/sec. In the example I'm about to show you, we've modeled a lateral-line canal as a simple tube with a series of pressure sampling points, or pores, and placed it 1 cm away from the source and parallel to the axis of vibration. Then we've simply used our computer program to calculate the pressure at each of these pores, using an interpore distance of 2 mm, the average interpore distance on canals of the mottled sculpin. The dotted line that you see here is a plot of those pressure values. But remember that the lateral-line system is a pressure-gradient detector, so we've also plotted the pressure difference between consecutive pore pairs – that's the solid line. As you can see, the pressure-gradient pattern consists of a large, central positive peak pointing directly at the source and surrounded by two, rather shallow negative troughs on either side. This means that fluid flow inside the canal is in one direction in the center of the canal and in opposite directions towards the ends of the canal. Remember that the peripheral lateral-line system is wired in such a way that this information is preserved.

With this kind of modeling approach, in combination with electrophysiological recordings from peripheral lateral-line nerve fibers, we've actually been able to demonstrate that patterns like this are faithfully encoded by the lateral-line system (Coombs et al. 1996[4]; Coombs & Conley, In Press[4]). Furthermore, by videotaping pathways followed by mottled sculpin when orienting towards dipole sources, we can actually 'visualize' how excitation patterns along the lateral-line system change as the fish approaches the source and, thus, as the fish changes its position in the dipole flow field (Coombs & Conley, In press[4]). These kinds of studies help us to determine the overall behavioral strategies used by fish when being guided by dipole flow fields (Table 3) and how the flow field and the information it contains about the source are encoded by the lateral-line system.

Actually, there's a lot more to this story than I have time to tell you, including how these patterns convey information about source distance and how sculpin orient to the flow lines. But let me stop here and make a few concluding remarks while you look at this final slide summarizing the basic features of the fish lateral-line system relative to the fish ear (Table 4). One is that at frequencies <200 Hz and at source distances <1–2 body lengths, it's almost a certainty that both the lateral line and the ear of fish will be stimulated. So at these frequencies, the important question is, what does the lateral-line system buy the fish that the ear doesn't? I think the simplest way of thinking about this is that the spatial distribution of endorgans and the biomechanical response properties of the lateral-line system mean that information in pressure-gradient patterns, like those you just saw, is available only through the lateral-line system. Thus, it would seem to me that in order to maximize our ability to design effective, sensory-based guidance systems, at least from a lateral-line perspective, we need to learn a lot more about (1) the kinds of pressure-gradient patterns fish encounter in their natural environment, including dam sites, (2) how different species and life stages behave in the presence of these patterns, and (3) how patterns are encoded by the nervous system and integrated with information from other sensory systems, including the ear, to effect behavior.

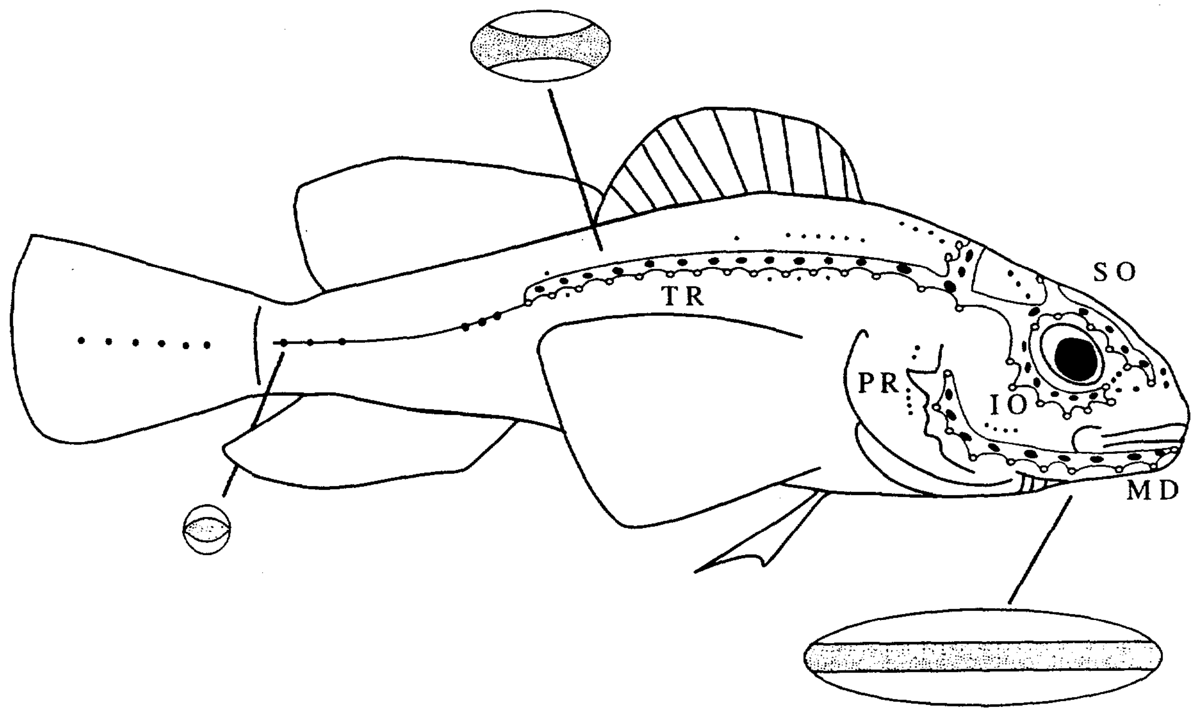

Figure 1

Schematic representation of the distribution of canal (large black circles) and superficial (small dots) neuromasts on the head and trunk of the mottled sculpin. Canal neuromasts form the trunk canal (TR) on the body of the fish and several canals on the head, including the preopercular (PR), mandibular (MD), infraorbital (IO), and supraorbital (SO) canals. Insets show a schematic and enlarged representation of the dorsal surface of neuromasts (cupulae removed) from several different body regions. These illustrate the relative size (not to scale) of a superficial neuromast at the base of the tail and of neuromasts from the trunk and mandibular canals. Stippled areas in each show the extent and orientation of the sensory epithelium (the hair cells). Note that the sensory strip in both canal neuromasts is aligned along the axis of the canal.

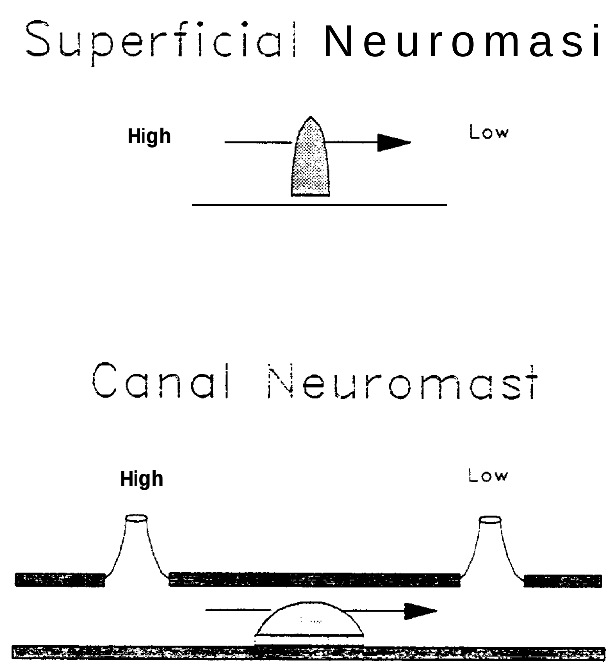

Figure 2

Schematic representation of how cupula movement in both superficial (top diagram) and canal (bottom diagram) neuromasts is coupled to the motion of surrounding water. The cupulae of both are thought to be driven primarily by viscous forces, resulting from the relative movement between the fish and the surrounding water. Water flowing over the skin surface of the fish from areas of high pressure to low pressure will couple directly to the cupulae of superficial neuromasts, causing the cupula to 'slide' over the neuromast. These same areas of high and low pressure will also induce fluid motion inside the canal, thus indirectly causing the cupula to slide over the neuromast.

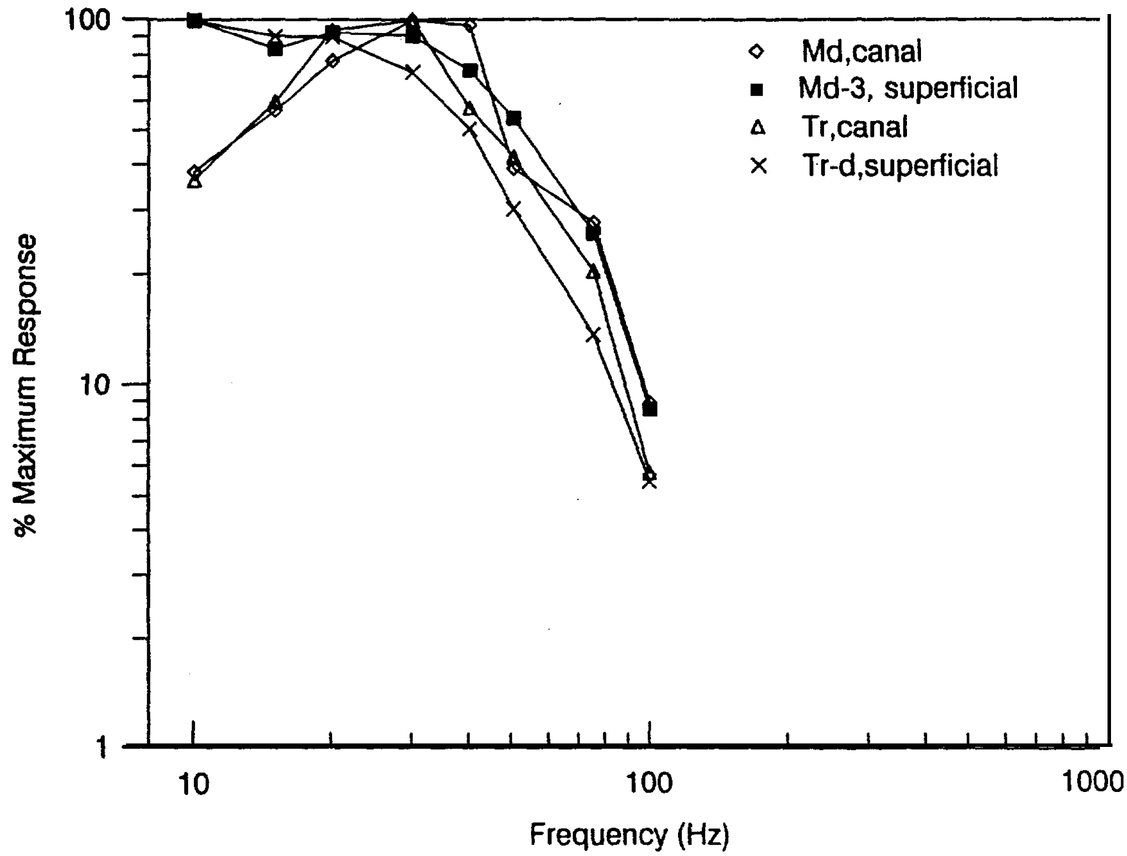

Figure 3

Comparative responsiveness of canal and superficial neuromast fibers when the lateral-line system is stimulated at different frequencies but at constant maximum-flow velocities (modified from Coombs & Montgomery 1994). Fibers innervating superficial and canal neuromasts were sampled from both the mandible (MD) and trunk (TR) region of an Antarctic fish. Responsiveness (measured in terms of evoked spike rate and degree of phase-locking to a sinusoidally-vibrating sphere) of fibers innervating superficial neuromasts (filled square and x) is relatively constant at -10-50 Hz, whereas responsiveness <50 Hz is reduced in canal neuromast fibers.

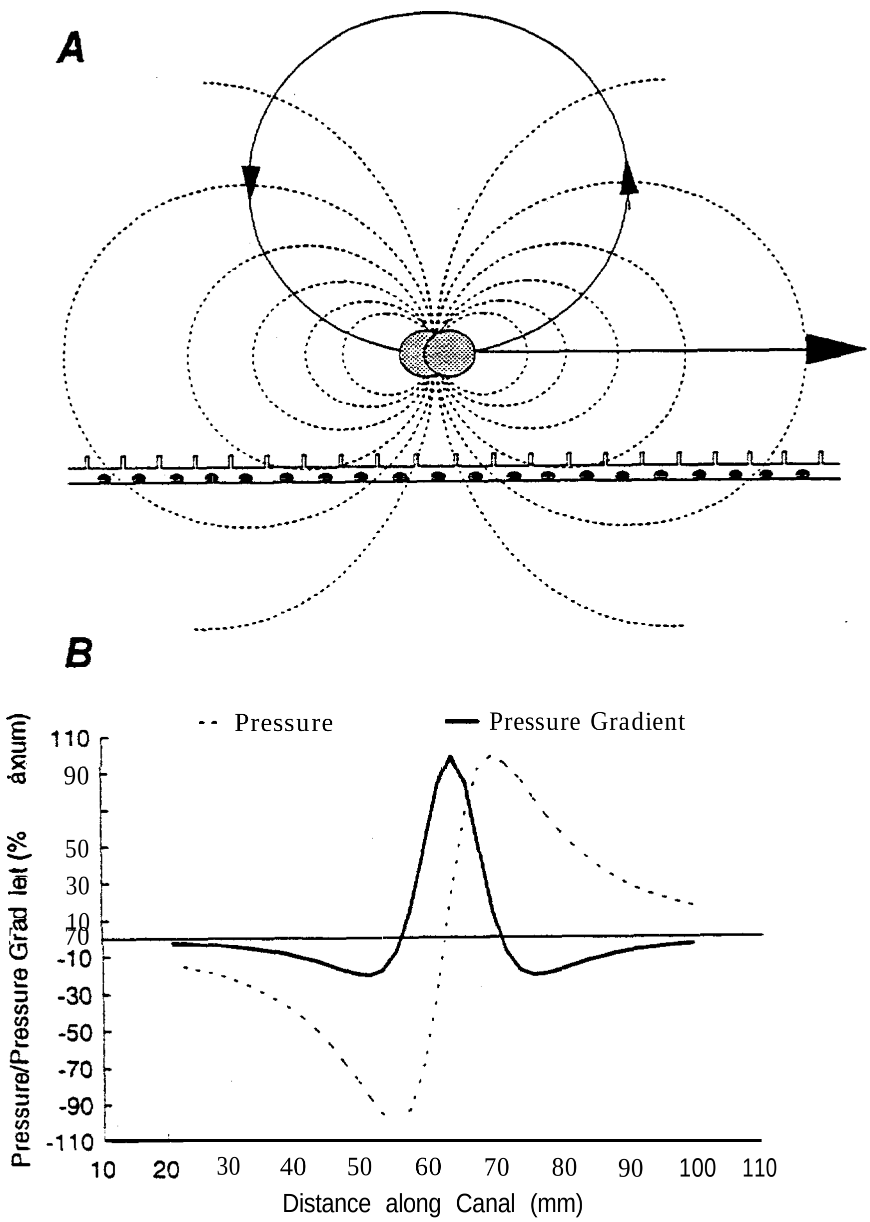

Figure 4

(A) Schematic representation of iso-pressure contours (dashed lines) and flow lines (solid lines with arrows) about a dipole source (filled circle in center), vibrating from left to right. **(B)** Corresponding plots of pressure (dashed line) and pressure-gradient (solid line) distributions across a trunk canal that is parallel to the axis of source vibration and in a plane that bisects the source center, as pictured in A. Note that the maximum pressure gradient in B is centered at the location of the source, arbitrarily located at x distance = 61 mm along the modeled canal. (Adapted from Coombs et al. 1996[4])

Table 1
Dimensions of morphological variation in the lateral-line system.

Canal structure

- Narrow canals with rigid (bone or scale) walls (probably most Columbia River species)
- Wide canals with compliant (membranous) walls (unknown among Columbia River species)

Pore/tubule structure

- Single pore with unbranched tubule (probably most Columbia River species)
- Branched tubules with multiple pores (most elasmobranchs and subeuteleostean fishes, e.g., Clupeiformes)

Swimbladder-bulla-lateral line system of clupeids

- Relative abundance of canal vs. superficial neuromasts

Canals absent or incomplete, often replaced by superficial neuromasts (pit lines)

(canals absent in early life stages of all fish)

(trunk canal absent in adult Clupeids)

(head canals incomplete in some adult Esocidae)

- Proliferation of superficial neuromasts (many cyprinids)

Table 2
Hydrodynamic sources of signals and noises.

Low frequency (<10 Hz)

Steady swimming motions (slow, regular power strokes) of fish and invertebrates
Ventilatory movements of fish and invertebrates
Laminar, non-turbulent, slow flows

Broadband or high frequency (up to 100-200 Hz)

Wakes (shed vortices) behind submerged obstacles in a stream
Wakes behind swimming invertebrates or fish
Turbent, fast flows

Table 3

Approach strategies used by sculpin in finding dipole sources.

- Move in directions that maintain a relatively small but constant pressure difference across the head and that progressively increase the pressure difference along the head.
- Align their bodies within 45” of the flow lines.
- Keep the source to the left or right side at an average angle of -30”.
- Avoid approach positions that are perpendicular to the flow lines and/or that place them in the pressure null zone of the flow field.

Table 4

Comparison of fish lateral-line and auditory systems (Coombs & Montgomery, In prep.)

	Lateral Line System	Auditory System	
Receptor Organs	Superficial and canal neuromasts	Otolifhic Ear	Air Cavity
Receptor Distribution	Dispersed on body surface	Clustered in cranial cavity	
Effective Stimulus	Differential movement between fish and sunounding waler	Whole body acceleration	Compression of air cavity
Stimulus Encoding	Pressure gradient patterns	Acceleration	Pressure fluctuations
Distance Range	1 Body Length	10 Body Lenglhs	100 Body Lengths
Frequency Range	cl Hz to 200 Hz	<1 Hz to 500 Hz	<1 Hz to 2000 Hz

Discussion of source distance relative to fish size

Abstract

Interpore spacings on canals may determine distance range of lateral-line system. Sheryl Coombs, Parmly Hearing Institute, Loyola University of Chicago. Soc. Neurosci. Abstr. 22:1819.

In most teleost fish examined to date, there is a single sensory organ (neuromast) between every two lateral-line canal pores. The response of any given neuromast to fluid motions inside the canal is proportional to the external pressure gradient across the two pores. Thus, the excitation pattern across neuromasts can be predicted by the pressure-gradient pattern across pores, which, in turn, will depend on the spatial interval between pores. To determine how interpore spacing might vary, we measured the distance between consecutive pairs of pores on the trunk lateral-line canal of 12 teleost species from six different orders. Mean interpore distances (IPD's) were computed for the trunk canal on one side of the fish for at least two individuals per species. Mean IPD's were strongly correlated with fish standard length (SL) both within and between species and varied from 0.8 mm for a blind cavefish (*Astyanax mexicanus*, SL = 40 mm) to 16 mm for an alligator gar (*Lepisosteus spatula*, SL = 1040 cm). Thus, mean trunk IPD's were nearly a constant fraction (between 0.01 and 0.02) of fish SL. To determine how lateral-line excitation patterns might vary for different IPD's, we also modeled the pressure-gradient patterns expected from a small (6 mm diam) 50-Hz dipole source. For a 2-mm IPD and source distances less than 80 mm,excitation patterns contained information about both source location and distance. At distances greater than *80* mm, the excitation pattern was relatively flat, meaning that this information was lost. For a 20 mm IPD, the excitation pattern did not flatten out until source distances greater than 160 mm. These results suggest that the distance range of the lateral-line system depends on IPD and, as such, depends ultimately on fish SL in widely divergent taxa. (Funded by grants from NIDCD and ONR).

* * * * *

I made the comment earlier that the distance range of the lateral-line system was tied to the length of the fish. And this might be important when you consider the distance an animal must be from a sound source, as a function of its life stage or species-dependent size differences. I want to bring you back to this particular demonstration **(slide)** in which we're mapping out the pressure-gradient pattern across the lateral-line canal. You can think of that in terms of the entire length of the fish, and you could simplify our modeling in terms of a single canal that extends the entire length of the fish. And you'll remember that I did this modeling for the case in which the interpore spacing was 2 mm. I did that for a specific reason, because that was the interpore spacing along the trunk canal of the mottled sculpin. NOM., the standard length of adult mottled sculpin is ~10 cm, and that means that this 2 mm is ~0.02 of the fish's standard length. We have measured the interpore spacing along the trunk for about 13 different species, and when you measure that on different sized individuals of the same species, or for different species in six orders of fish, you find that this inter-pore distance is typically a constant fraction of standard length, between 0.01 and 0.02.

So what happens to this pressure-gradient pattern when you move this canal further away from the source? **(slide)** This is the color-spectrum representation of the pressure-gradient pattern, and here's our positive red pressure gradient in the center, with our two negative pressure-gradient troughs that surround the peak – that 'Mexican hat' picture of the pressure-gradient pattern. Now let's double the distance from 1 to 2 cm. As you can see, there's a spatial dispersion in this excitation pattern, so that central peak is now broader. Let's double the distance again. Again, there is spatial dispersion. We're now at 4 cm from the source. By the time you get to -8 or 16 cm from the source, which is -1 or 1.5 body lengths, basically that pattern completely flattens out so that the information there about the source distance completely disappears. The idea is that there are separate channels going to the central nervous system and that they retain their respective positions as they form a ‘map’ of the peripheral excitation pattern.

I’ve just shown you the pattern that results when there are 50 neuromasts or 50 pores across the fish at 2-n-m interpore intervais along a fish that is -10 cm long. But now we’ve got a bigger fish, -100 cm long, with a 20-mm interpore spacing. This is what the excitation pattern looks like for the bigger fish. And as you can see, for a given source distance and amplitude, the pressure-gradient pattern ‘seen’ by the larger fish contains a sharper, more enhanced image of the source relative to that ‘seen’ by a smaller fish, assuming that patterns are mapped similarly in the central nervous system.

The last thing I need to show you is what happens to these patterns as a function of distance. And to do that, let me just draw out the same kind of picture where we’ve got neuromast number along this axis, and pressure-gradient amplitude along this axis, and now we’re going to keep the source distance constant. Let’s say it’s at 40 mm away, or 4 cm away. So here’s the pattern you would see, for example, for an interpore spacing of 2 mm for our 10-cm fish. Here’s the pattern you would see for our 20-mm spacing for our larger fish. And I’m just showing you a small fraction of the pattern now. The point of this slide is that the peak amplitude of the pressure-gradient pattern for the larger interpore spacing is much greater than that for the pattern determined by the smaller interpore spacing.

Now let’s draw the same picture again at a source distance of 80 mm. And by this time, the pressure-gradient pattern for the small fish with 2-mm interpore spacing is essentially flat. In other words, there’s no information at all in the pressure-gradient pattern. But for our larger fish, we still have quite good information about the source. And that’s the point I wanted to make. Information about source distance contained in excitation patterns is tied to the size of the fish, such that larger fish can detect sources farther away than smaller fish. It has to do with the fact that the interpore spacing is a constant fraction of the animal’s standard length. And that’s probably just a morphometric consequence of some fundamental, developmental rule.

MR. DOUST: Is that basically a resolution factor? You’re talking about different scales of lateral-line separations, right?

DR. COOMBS: Just different interpore spacing. I think it keeps size constancv as the fish grows. In other words, the image of the source contained in the excitation pattern is scaled to the size of the fish.

MR. SCHILT: And does frequency have anything to do with this?

DR. COOMBS: No.

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Sound Detection by Fish: Structure and Function

Dr. Arthur N. Popper
University of Maryland at College Park

We will now discuss the inner ear. The ear is involved in detection of signals coming from a range of distances that overlap, but extend much further than, the distances to which the lateral line responds. The ear also provides, we believe, a general 'impression' of the acoustic environment of the fish, just as our ears not only provide information about speakers and music, but also give us a sense of the overall environment.

First we will look at how well fish hear. This is demonstrated in a set of hearing curves or audiograms (Figure 1) which show frequency vs. threshold, or the minimum sound level that the fish or any organism can detect at each frequency (see presentation by Dr. Fay for more details). I want to illustrate a couple of points in this figure, particularly the difference between what we call hearing specialists and non-specialists. Hearing 'specialists' are species with special adaptations that enhance hearing ability (both bandwidth and sensitivity) over that of other species, 'non-specialists', which have not evolved mechanisms to enhance hearing. For example, data for the Atlantic salmon, *Salmo salar* (Hawkins & Johnstone 1978), show that this species is a non-specialist and can hear sounds only up to 400 or 500 Hz, with best hearing in the range of 100-200 Hz. More recent work (Knudsen et al. 1994) shows that this same species can detect sounds at much lower frequencies (infrasound).

In contrast, the goldfish, *Carassius auratus*, a hearing specialist, has much better hearing sensitivity and a wider bandwidth than the salmon, and can hear up to 2000–3000 Hz. The goldfish is what we call an 'otophysan' fish. Otophysans also include the squawfish, a prominent predator in the Columbia River. Figure 1 also shows data for *Myripristis berndti*, a squirrelfish from Hawaii (Coombs & Popper 1979). The reason 1 want you to see this is that the hearing capabilities of this squirrelfish are similar to that of the goldfish. The significant point is that the two species are taxonomically unrelated. While their hearing capabilities are very similar, the mechanisms that these hearing specialists use to achieve this excellent hearing are very different.

Figure 1 also shows an audiogram for a perch, *Perca fluvitalis*, a hearing generalist (or non-specialist), that does not hear very well (Wolf 1967). The figure also shows *Adioryx xantherythrus*, another squirrelfish that, while related to *Myripristis*, does not hear very well (Coombs & Popper 1979). While *Myripristis* has specializations that make it a hearing specialist, *Adioryx* does not have the same adaptations and so is a non-specialist. The point I want to make from this figure is that we have hearing specialists that can hear up to several thousand Hz, and hearing non-specialists that cannot hear higher than 500-700 Hz. Again, thresholds art' quite different between them.

Figure 2 shows the structures of the auditory system in a hearing specialist. The basic structure, other than the bones connecting the swimbladder to the ear, applies to non-specialists as well. There are no external structures or ear canal. The ear is located in the cranial cavity. Hearing specialists have some kind of structure that brings an air bubble physically, or at least acoustically, close to the ear, whereas in hearing generalists the ear and any air bubble are relatively far apart and not coupled acoustically. The analogy is the middle-ear bones of terrestrial vertebrates which connect the tympanic membrane with the inner ear. In the case of the otophysan fishes, there is a series of bones called the Weberian ossicle that serves as a pseudo middle ear and connects the swimbladder, an air-filled chamber found in the abdominal cavity of the majority of fish species, physically and acoustically to the inner ear.

Acoustic coupling between the ear and an air bubble varies in different hearing specialists. In the case of the squirrelfish *Myripristis*, the swimbladder actually projects rostra1 ly and makes contact with the part of the skull very close to the ear. This adaptation is not found in *Adioryx*. In the herrings, i.e., the clupeids, the bubble actually projects right into part of the ear. Examination of a wide range of fish species will reveal a variety of adaptations that enhance hearing, and it appears that fishes with such adaptations hear over a wider range of frequencies and have better hearing sensitivity than fishes without such adaptations (Popper & Coombs 1982).

Figure 3 shows the ear of an Atlantic salmon (redrawn from Retzius 1881). The ear is typical of other vertebrate ears in many ways. The major morphological difference between the mammalian and fish ear is that in fishes the ear lacks a cochlea but has three, rather than two, otolithic organ. Fishes have three semicircular canals that detect angular acceleration (Platt 1983) and three otolith organs: the utricle, the saccule, and the lagena. Classically in the literature, the saccule has been considered the auditory endorgan and the utricle more for detection of body position. The function of the lagena was never well defined, though there have been some suggestions that it is involved in audition.

More recently, however, our views on the function of the three otolithic organs have changed, based upon a wealth of new data. It now appears that all three otolith endorgans have multiple functions. In other words, all may have some vestibular and some auditory function. While one endorgan may do more than the other in terms of hearing, this may vary depending upon the species. So in some species the utricle may be the major hearing organ, in others the saccule.

Each otolithic endorgan contains a single calcareous otolith that is several times denser than the rest of the fish's body. The otoliths lie very close to a sensory epithelium (or macula) (Figure 4). The sensory hair cells are part of the sensory epithelium, and their cilia contact the otolith. Any relative motion between the epithelium and otolith will result in a bending, or shearing, of the cilia and this results in a change in the receptor potential of the cell. This, in turn, excites neurons of the eighth cranial nerve which innervate each sensory hair cell.

Figure 5 is a schematic representation of the saccular and lagenar sensory epithelia and the hair cell orientation patterns from a salmonid, *Coregonus clupeaformis*, the lake whitefish (Popper 1976). It shows the saccule and lagena in the same chamber. Typically, in the saccular epithelium of a non-otophysan fish – i.e., a fish that's not a goldfish, a squawfish, or a catfish – the hair cells are oriented in four directions: rostral, caudal, dorsal, and ventral.

The lagena generally has hair cells oriented dorsal-ventral, but the epithelia also curve, resulting in hair cells oriented in a variety of directions. The relative sizes of the saccule and lagena in the lake whitefish, with the saccule being much larger, is typical of other non-otophysan fishes. In otophysans, as demonstrated by the goldfish (Figure 6), the lagena has about the same epithelial area as the saccule. The functional significance of the difference between non-otophysans and otophysans is not yet clear, but one suggestion has been that the saccule and lagena in otophysans have significantly different auditory roles than in non-otophysans (Popper & Fay 1993).

In fact, one of the things we have seen in looking at fishes over the years is a wide variability in structure of the ear among different species (e.g., Popper & Coombs 1982, Popper & Fay 1993, Popper & Platt 1993). We almost always see differences in the endorgan among fishes, which we most closely associate with hearing in a particular species. That is, in most fishes the most extensive interspecific variation encountered is with the saccule, the endorgan that is likely to have a major hearing organ in many species.

This hypothesis is strengthened by two exceptions. One is in several species of marine catfish, where the utricle appears to be involved in detection of low-frequency sounds (e.g., 200 Hz) (Popper & Tavolga 1984). In these catfishes, the utricle is extraordinarily large, and there are several unique features to the sensory epithelium. In fact, we suggested that the utricle in these species may have evolved into an excellent accelerometer for low-frequency detection. Interestingly, these species use low-frequency sounds to 'navigate' (Tavolga 1977). The second example is found in the clupeids, the herring-like fishes. In the clupeids, a small air bubble, connected via a thin tube to the swimbladder, lies intimate to the utricle, and not the saccule (Blaxter et al. 1981). The saccule in clupeids is not very different from that in hearing generalists, while the utricle has characteristics that resemble the saccule in hearing specialists (Popper & Platt 1979). The clupeid's utricle is absolutely unique among vertebrates

Based upon the uniqueness of the utricle, it has been suggested that clupeids are hearing specialists (e.g, Blaxter et al. 1981). However, very little is known about hearing in any member of this group of fishes, and we do not know if any species can detect sounds in the same range as found in other hearing specialists. The data on hearing in herring are physiological (Enger 1967) and, as such, do not provide a real measure of behavioral-response capabilities of the fish. At the same time, there are a number of recent papers that suggest that at least some clupeids can detect and respond to ultrasonic sounds (upwards of 120 kHz) (e.g., Nestler et al. 1992), although there are no data to suggest how these sounds are detected.

While the hair-cell orientation patterns of the utricle and lagena tend to be conservative in structure among most teleost fishes, the saccule has tremendous variability in orientation patterns in different species (e.g., Popper & Coombs 1982, Popper & Platt 1993). After examining the saccules of many species, we noticed that there are really several different hair-cell orientation patterns among these groups (Figure 7). Significantly, many of these patterns transcend taxonomic lines, with very similar patterns found in totally unrelated species. The suggestion is that similar patterns have been derived several times among teleosts. Moreover, the most common 'standard' pattern is found only in hearing generalists, the four or five variants shown in Figure 7, are found only in hearing specialists. Although we have no data to suggest the functional significance of the various patterns, we have speculated that fishes with different saccular patterns have either evolved different ways of doing the same acoustic tasks with their saccules or, conversely, they are all extracting different types of information about signals.

We will now consider how sound gets to the ear in fishes. It appears clear that fishes are able to detect sounds in two ways: direct and indirect (Figure 8). Some fishes use only indirect stimulation, while other species (and especially the hearing specialists) use both direct and indirect. To understand these systems, it is necessary to keep in mind that the otolith is three or more times denser than the rest of the fish's body.

When a sound field impinges upon a fish, as Mardi Hastings pointed out earlier, the fish's body, including the sensory epithelium, being of the same density as the water, moves with the sound field. But the otolith, being much denser than the rest of the body, tends to lag the movement of the epithelium. Since the ciliary bundles are, in effect, attached at one end to the sensory epithelium (via the sensory hair cell) and at their tips to the otolith, the cilia bend in response to the relative motion between the otolith and the epithelium. This results in stimulation of the sensory hair cells. This is the basic mechanism of direct stimulation of the ear. In such cases, the particle-displacement component is responsible for inner-ear stimulation, and the ear is capable of detecting the direction of the signal.

The pressure signal, in contrast, stimulates only the air-filled swimbladder (or other air bubble). The motions of the wall of the bubble reradiate energy in the form of particle displacement, and this is detected by the saccule or by some other endorgan. This provides both direct and indirect stimulation, but you need to have a swimbladder to get the indirect stimulation. The suggestion is that only in hearing specialists, where the air bubble has some acoustic coupling to the inner ear, do you get indirect stimulation by the swimbladder.

Earlier I mentioned the hair-cell orientation patterns on the otolithic endorgans. The significance of this is related to the direct stimulation of the ear and the mechanism by which it is generally believed that fish get some information about the direction of a sound source (sound-source localization). In the case of the saccule, the directionally-sensitive hair cells give their maximum response when the direct signal is along the axis of best response of the hair cells (Figure 9). If the signal is off of this axis, the signal is less than when it is on the axis. No matter what direction the stimulus comes from around the epithelium, the ear itself can resolve potentially directional signals by comparing information from one orientation group of hair cells with information from another group. Even more information is provided when we consider that there are additional 'sub-groups' of hair cells on a single epithelium as a result of curvature of the epithelium, and even more information comes from all three endorgans and the two ears. Thus, a signal from any direction will present an array of different responses from hair cells oriented in a variety of different directions (see Schellart & Popper 1991, Popper & Fay 1993). In theory, the fish brain gets information from a wide range of hair-cell groups. In other words, theoretically the brain looks at the output level from different regions with different hair-cell orientation patterns and can calculate the direction of stimulation (Popper et al. 1988, Rogers et al. 1988). Again, there arc other issues like ambiguities between front and back (Schuijf & Buwalda 1980, Schuijf 1981) which we won't get into.

Up to now I have reviewed basic information about fish ears and fish hearing. Now 1 want to spend a bit of time dealing with several issues that are under current study in my laboratory, and which are germane to our understanding of how fishes detect sounds and how sounds might affect fish sound detection.

The first issue I want to deal with concerns the number of sensory cells on the sensory epithelium. In several studies (Popper & Hoxter 1984, Lombarte & Popper 1994), we investigated the size of sensorv epithelia in different sized fishes and the number of sensory hair cells as animals grow. The results are demonstrated best from a study of the European hake, *Merluccius merluccius* (Lombarte & Popper 1994). We found that each of the otolithic endorgans grows significantly over the lifetime of the hake, and a similar phenomenon has been found in other species such as the oscar (Popper & Hoxter 1984) and goldfish (Platt 1977), as well as in several salmonids (Song & Popper, in prep.). Our results are graphed in Figure 10. We found that as hake grew, there was a very substantial increase in the number of sensory hair cells. In fact, animals about 6 months old had -25,000 cells in a single saccule, while over 1 million were found in the saccule of animals 9 years of age. Contrast this to the fact that the increase in hair cells in amphibians is only several hundred over a lifetime (Corwin 1985) and may not even occur in mammals or in avian auditory endorgans (Corwin & Warchol 1991). In fact, as humans age we actually lose hair cells due to damage or just the aging process. The only comparable results are for elasmobranchs, where hair cells also increase at a prodigious rate (Corwin 1981, 1983).

The point here is that as fishes grow they add large numbers of sensory hair cells. The obvious questions concern the functional significance of hair cell addition. There are two hypotheses. One is that the addition of hair cells enhances hearing abilities in older fishes. But that makes little sense because you would imagine that there is some selective disadvantage to constantly having a different hearing ability. The alternative (Popper et al. 1988, Rogers et al. 1988) suggests that the relative sizes and structures change position as a fish grows, and the role of cell addition is to maintain the same ability to hear. We have not tested either hypothesis, but both are of considerable interest.

The second study I want to mention has direct bearing on the potential use of sound in the control of fish behavior. My lab, in collaboration with that of Mardi Hastings, has been examining the effects of very intense sounds on the fish octavolateralis system (Hastings et al. 1996). Very briefly, we stimulated oscars, *Astronotus ocellatus*, with fairly high-intensity sounds at several different frequencies for 1 hour and then examined the effects on the sensory hair cells of the ear and lateral line using scanning electron microscopy. We found that after l-hour noise exposure at 300 Hz at 180 dB//1 µPa followed by a 4-day survival time would result in damage to the sensory cells of the lagena. Damage was not found with other frequencies, lower intensities, sounds with a 10% duty-cvcle, or if the fish were not kept for 4 davs after stimulation. Still, there is some evidence that intensity sounds may cause some damage in fishes that hear better than oscars (e.g., in hearing specialists) (Cox et al. 1986a, 1986b, 1987). Our results clearly demonstrate that under certain very specific conditions, and for a single species, sound can damage the ear. Whether these results are applicable to shorter sounds, or to sounds at different frequencies, is still not known. Moreover, looking at the fish just a short time after stimulation may not be appropriate because, in fact, it may take a while for the trauma caused by the intense sound to show up.

After we started learning more about fish-passage problems, we realized that WC are dealing not only with fishes that move away from sounds, but that we should also be concerned with organisms that cannot or do not move away from the ensonification. If, and how, these organisms are affected by the ensonification is not known, but we do know from studies on mammals that long-term exposure to moderately high sounds can result in long-term hearing loss.

One thing that confounds these results and makes it particularly difficult to ascertain the effects of intense sound stimulation on fish is the finding that hair cells regenerate in fishes after they have been damaged, at least when the trauma is caused by drugs. This was demonstrated in'a study where we injected fish with the drug gentamicin sulphate, one of a group of drugs that are known to damage sensory hair cells of the ear (ototoxicity). After several days of gentamicin, one region of the utricle of the oscar – the striola – has lost all of its hair cells (Yan et al. 1991). A similar experiment demonstrated that hair cells of the lateral-line canal also are damaged (Song & Popper 1996). In both bases, however, the damaged hair cells regenerated after about 10-15 days following the termination of drug treatment, suggesting that fishes, unlike humans (but like birds and amphibians), can regenerate hair cells that have been damaged.

In conclusion, fish have a wide range of variation in hair structure. There are many questions that need to be considered in the future, both about the basic biology of fish auditory mechanisms and hearing capabilities (see Popper & Fay 1993) and about applied aspects of the biology of fish hearing. Some of the questions most germane to the issues brought up at this workshop relate to the biological effects of sounds on fish behavior and physiology, and on the ability of fish to withstand the effects of these sounds either through behavior (e.g., moving away) or regeneration of damaged cells.

Figure 1
Behaviorally determined auditory thresholds (audiograms) for representative teleosts. Hearing specialists include the goldfish, *Carassius auratus* (Jacobs & Tavolga 1967) and the squirrelfish, *Myripristis berndti* (Coombs & Popper 1979). Hearing generalists are the Atlantic salmon, *Salmo salar* (Hawkins & Johnstone), the perch, *Perca fluvitalis* (Wolf 1967), and another squirrelfish, *Adioryx xantherythrus* (Coombs & Popper 1979).

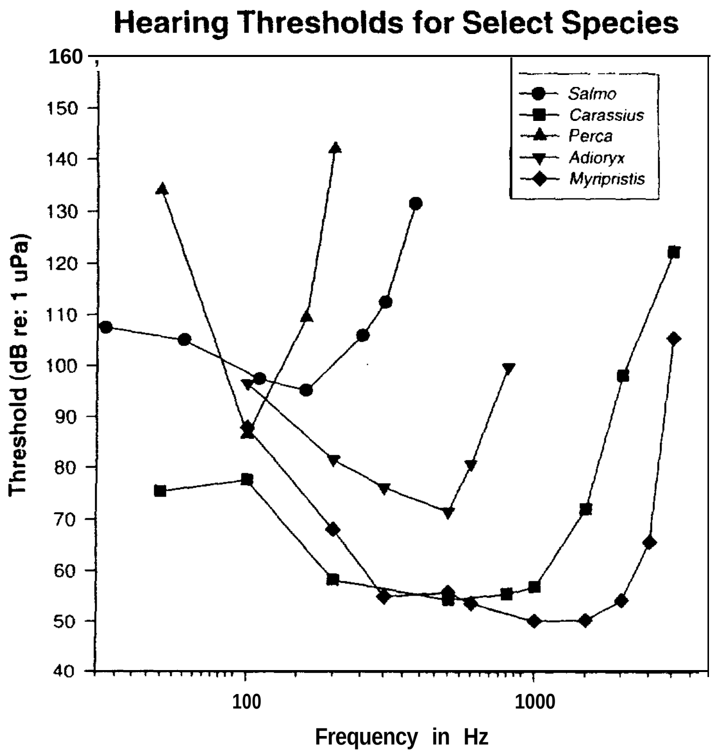


Figure 2
The peripheral auditory system in an otophysan fish showing the swim-bladder (SB) and its connection to the inner ear via the Weberian ossicles (TR, R, T, I, SC, ANT, AT, L2, L3, L4). Movement of the swim-bladder walls (IT and ET represent inner and external tunica of the walls) results in motion of the posterior-most ossicle, the tripus (TR), which is transferred via ligaments L1 to L4 to the anterior-most ossicle, the scaphium (SC). This motion, in turn, causes fluid movement in the sinus impar (ASI and SI) and the endolymphatic sac (ES), resulting in fluid motions in the transverse canal (TC) and, finally, in the saccule (S) of the two ears. (From Popper 1971; used with permission)

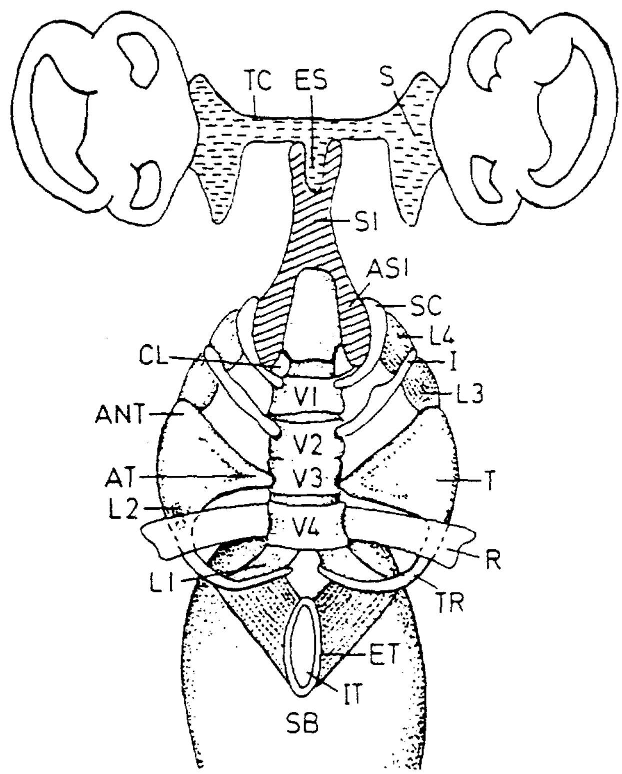


Figure 3

Medial view of the right ear of the Atlantic salmon, *Salmo salar.*, showing the sensory maculae and the innervation by portions of the eighth nerve. Anterior is to the left; dorsal is to the top. aa = anterior ampulla of the semicircular canals (not involved in audition); ap = posterior ampulla; ca = anterior semicircular canal; cp = posterior semicircular canal; ms = saccuiar macula; u = utricular macula; pl = lagena; s = saccule. (Redrawn from Retzius 1881)

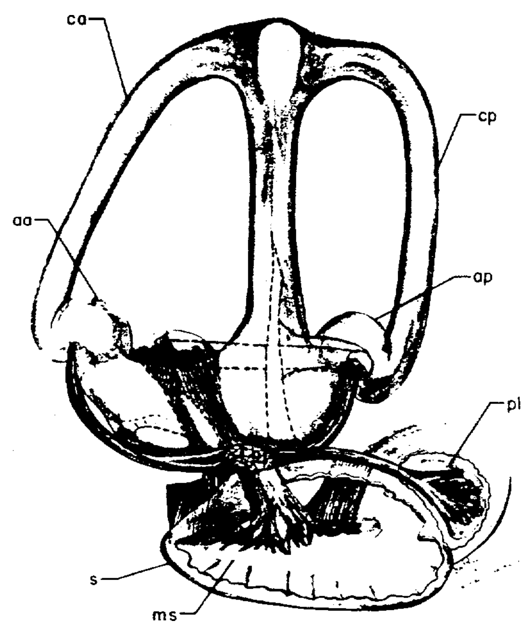


Figure *4*

Scanning electron micrograph of the surface of a sensory epithelium, showing the ciliary bundles on several sensory cells. Each bundle has a single kinocilium (longest cilia) and multiple stereovilli (or stereocilia). Directional orientation of cells is indicated by arrows on either sides of the dashed line (From Popper 1983; used with permission)

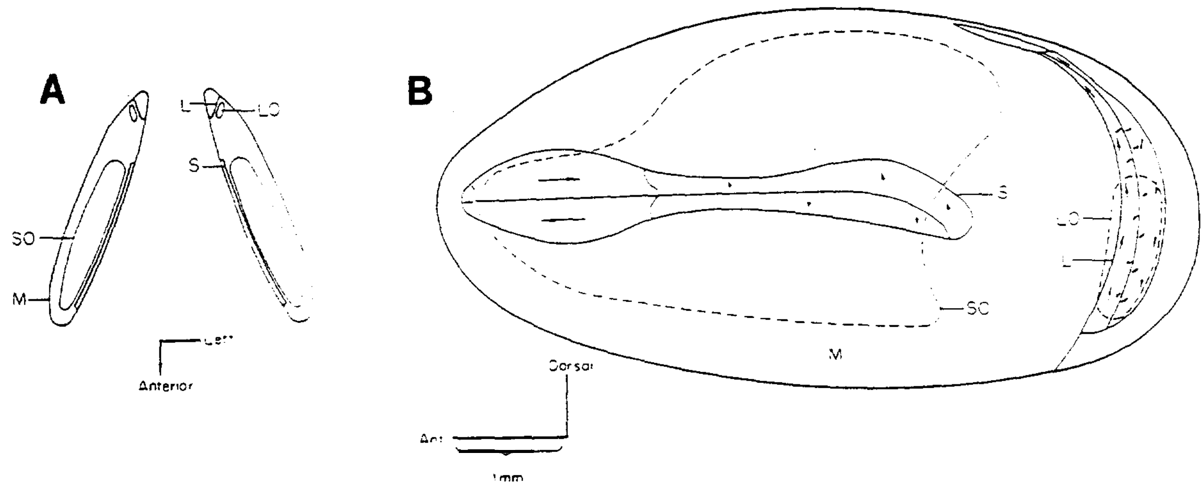


Figure 5

Saccule and lagena from a salmonid, the lake whitefish, *Coregonus clupeaformis*. (A) Dorsal view of the two ears showing how they are oriented as mirror images of one another. **(B)** Lateral view of the left saccule and lagena. Arrows on the maculae show the orientation of the hair cells as defined by the location of the eccentrically-placed kinocilium on the ciliary bundle (see Figure. 4). Dashed line shows the position of the otoliths. L = lagenar macula; LO = lagenar otolith; M = margin of the membranous labyrinth; S = saccular macula; SO = saccular otolith. (From Popper 1976; used with permission)

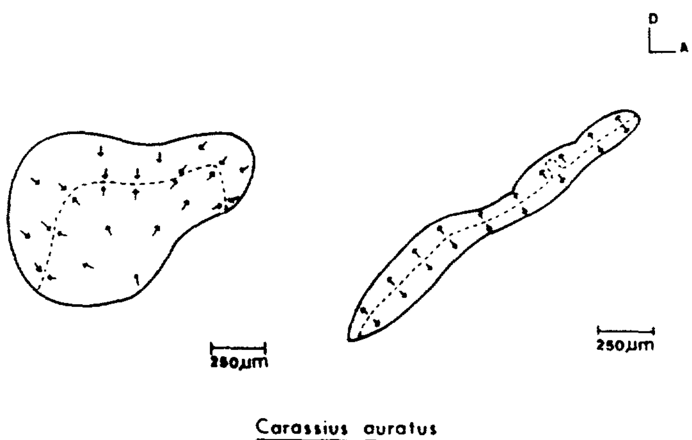


Figure 6

Hair-cell orientation patterns from the saccule (right) and lagena (left) from a hearing specialist, the goldfish *Carassius auratus*. Dashed lines separate different hair-cell orientation groups; arrows show orientation patterns of ciliary bundles (see Fig. 4).

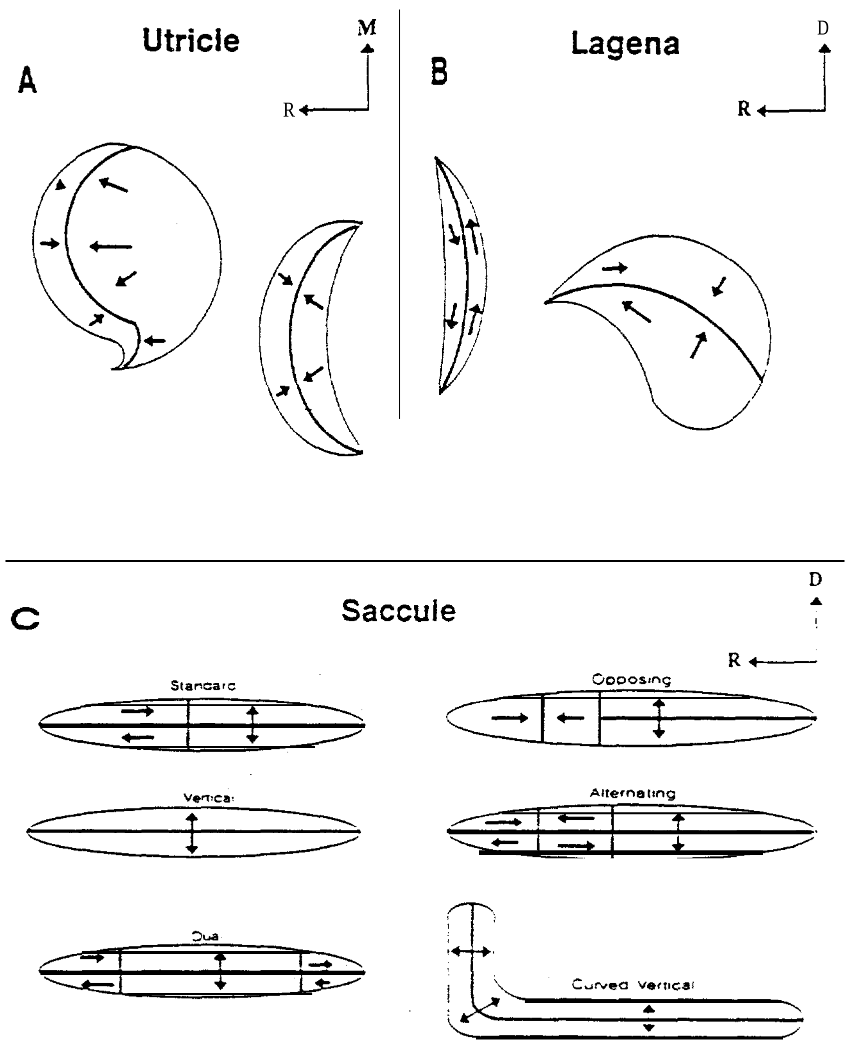


Figure 7

Schematic illustration of the different types of hair-cell orientation patterns that have been identified in each of the otolithic endorgans of different fish species. Arrows indicate orientations of the ciliary bundles on the hair cells in each epithelial region. **(A)** Two different utricular patterns. The one on the left is the most common found in bony fishes and tetrapods, while the one on the right is found in a few species that may use the utricle for sound detection. **(B)** The lagenar pattern on the left is the most common among fishes (but not found in tetrapods) while the one on the right is typical of otophysans. These hearing specialists may use their lagena much more as an auditory endorgan than in other fishes. **(C)** Six different patterns of saccular epithelia that have been identified by Popper and Coombs (1982). D = dorsal; M = mediolateral; R = rostral. (From Popper & Platt 1993; used with permission)

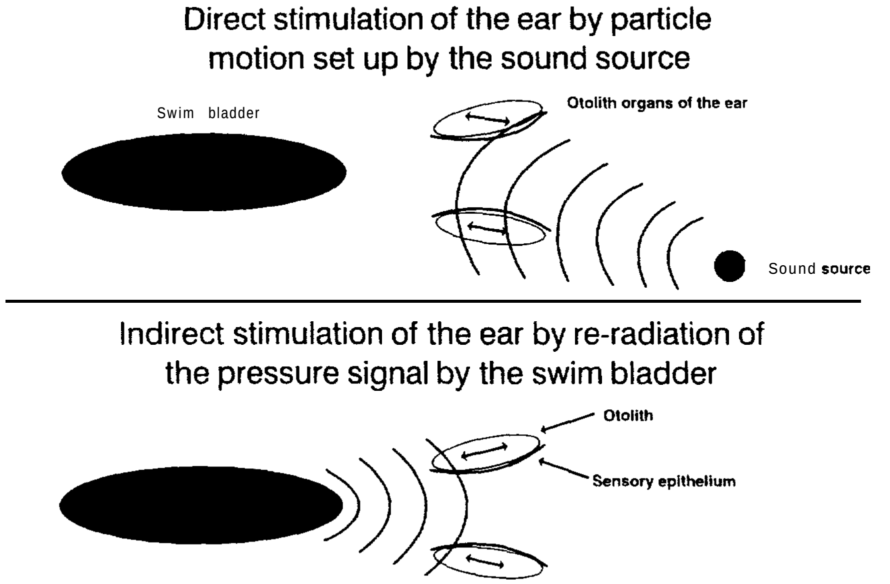


Figure 8

Illustration of direct and indirect stimulation of the ear. In direct stimulation (top), the particle displacement produced by the sound source results in relative motion between the otoliths and the sensory epithelium (see text). In indirect stimulation, the pressure signal from the same sound source (not shown) causes motion of the swimbladder walls and this produces a particle-displacement stimulus that is reradiated to the ear.

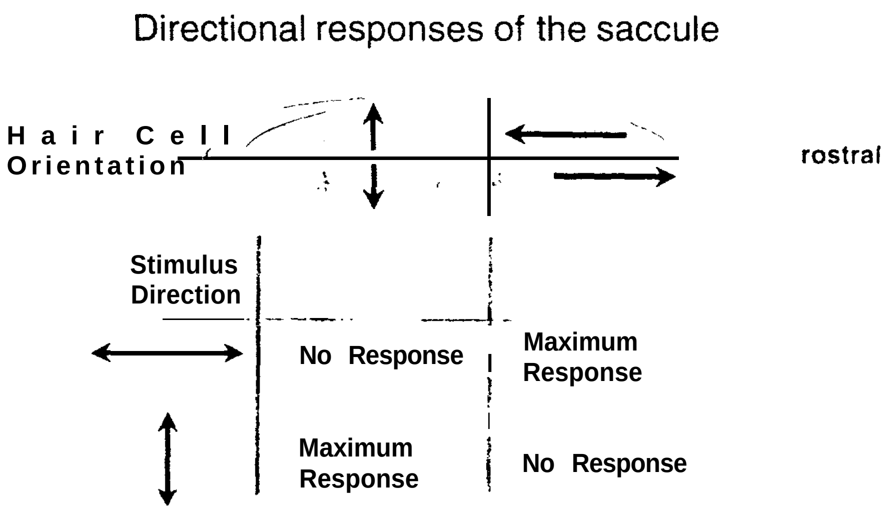
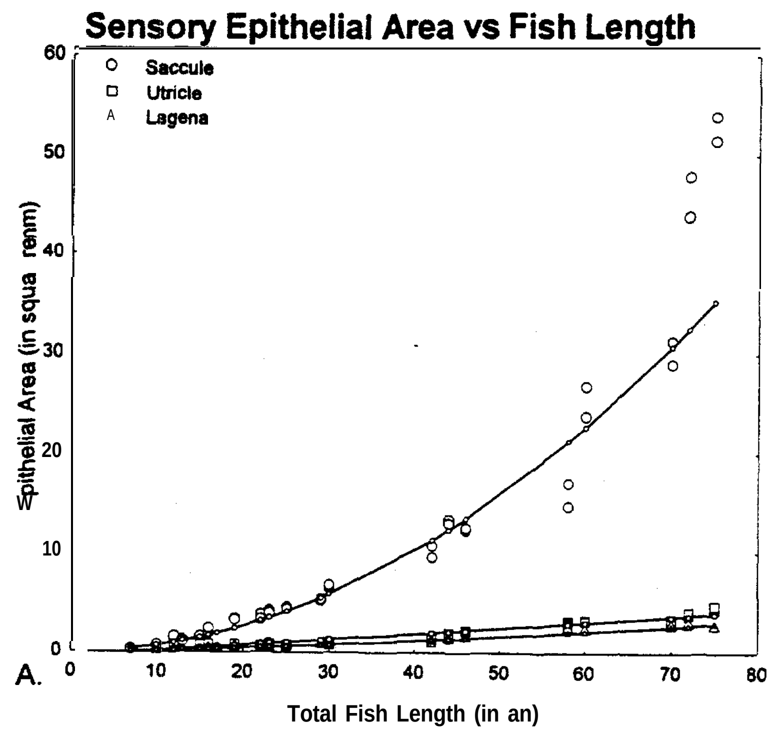


Figure 9

Direct stimulation of the ear results in relative motion of the otolith and the sensory epithelium. In this figure, the top illustration shows the hair-cell orientation pattern of a typical saccule. The lower table shows the kind of response that would be recorded from the caudal vs. rostral regions of the epithelium to stimulation from different directions. Recordings would be from the eighth nerve in response to the shearing action on hair cells.



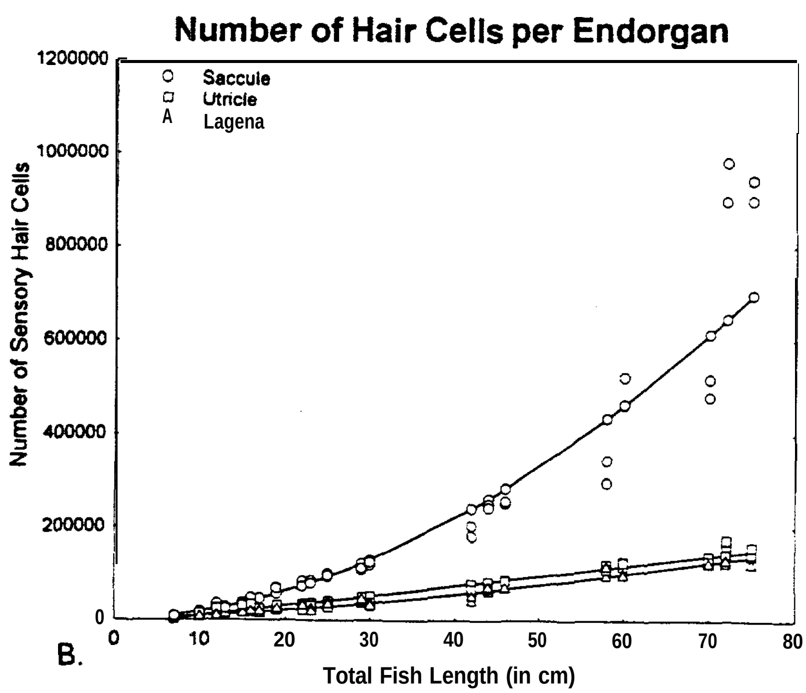


Figure 10

Changes in the size of the sensory epithelia (A) and number of hair cells per endorgan **(B)** with age of the hake, *Merluccius merluccius*. Lines are best-fit regressions. Each data point represents a single animal. (From Lombarte & Popper 1994; used with permission)

What Fish Hear

Dr. Richard Fay
Loyola University of Chicago

I'm going to talk to you today about the work I do in my lab that attempts to understand the fish's sense of hearing. If you introspect, you can ask, what is the act of hearing for humans? When I introspect, I come up with the idea that the act of hearing gives me knowledge about objects and events in my environment, although I don't necessarily do anything about it. In other words, it may or may not lead to an overt behavior. And I think the same thing's true about every other organism. Organisms may hear, they may obtain information, but they don't necessarily do anything. And this is the problem that many of you have, because you want to figure out how to make the fish do something in response to sound.

I'm going to talk today about what I think fish know, in some sense, about sound. It's another question to figure out how we make them act on the basis of their knowledge. Although the nature of human hearing can be understood by introspecting, the systematic and quantitative study of hearing in other organisms must be inferred from behavioral measurements. You must make the animal respond in order to know that they even hear. I'm a psychologist, and I'm going to talk about some psychophysics experiments that trick the organisms into responding. Psychophysics, which began over 120 years ago, was the foundation for experimental psychology in Germany and is still an important part of experimental psychology. Psychophysics measures the performance of an organism in detecting or discriminating sensory stimuli, and we will stick to sound in our case. Psychophysics can be used to determine absolute and differential thresholds, the minimum stimulus values required to produce a given level of performance.

In human psychophysics, all you have to do is ask someone to respond, to push this button if "yes," that button if "no." In animal psychophysics, you must condition or train the animal to respond. Performance of the animal is usually measured as the latency, the magnitude, or probability, of a conditioned response that has come under the control of, or is now signaled by, a sound stimulus. The usual focus of psychophysical studies is to determine what the animal is capable of detecting or discriminating, rather than what the animal normallv does in its usual environment. This is the limitation of our approach: It's one question to know what fish *can* do; it's another question, and another kind of experiment, to know what fish normallv Jo.

My goal in presenting this is to convey to you what's known about hearing in fishes and to characterize their senses of hearing, using psychophysical experiments. All quantitative data published on behavioral studies of fish hearing (and all vertebrate hearing) has been reviewed in Fay (1988). This book includes all data in graphic and tabular form. (Contact Dick Fav at rfay@luc.edu if you would like to purchase a copy.) This may be of some help to those of you who are interested in conducting field tests in the selection of stimuli and the design of experiments for influencing the behavior of fish using sound. My own view is that consideration should begin with stimuli that are known to be highly detectable, discriminable, and localizable in the presence of the usual ambient noise.

I want to first talk briefly about some of the many methods used in laboratory studies of the fish's sense of hearing. Figure 1 shows a goldfish placed in a little cloth bag, not rigidly restrained. It just sits there and respirates, opening and closing its mouth and pumping water. If you insert a thermister at the mouth, you can measure the water flow and the fish's respiration. If you produce a mild electric shock across the fish, it causes an unconditioned reduction in respiration and a decline in heart rate. Many experiments have been done using the heart-rate response; the two go together. The shock occurs, and for a few seconds the respiration goes to zero and then picks up again. In a detection experiment using Pavlovian conditioniing, these tone bursts become an acoustic signal that signals the electric shock. This signal takes on some of the characteristics of the electric shock and causes a suppression of respiration. So we know the animal heard that signal because its respiration is suppressed according to some statistical criteria. You can take a naive animal that has not been trained, and in about 20 minutes get them to do this, and an hour later you have some thresholds measured.

Figure 1 illustrates some of the psychophysical experiments we've done. In a frequency-discrimination experiment, the animal hears a constant 'beep-beep-beep' in the background. In this case, the acoustic signal that signals shock is the change of the frequency of the tone. When the tone changes and the animal drops its respiration, we can say that it discriminated between two frequencies. In a level- or intensity-discrimination experiment, there is the same constant 'beep-beep-beep' in the background; however, rather than changing the frequency, we change its loudness or intensity level, and a conditioned response tells us that the animal discriminated between two levels of loudness or intensity. In a masking experiment, we have this background 'beep-beep-beep' that is actually a masker or noise, and we have the signal that is this 'pip' embedded in the noise. When we add the signal to the background noise, and the animal suppresses its respiration, we can say that the animal detected that acoustic signal in the presence of the noise. Another experiment that I call 'temporal-pattern discrimination' is where you have a constant-rate 'put-put put-put-put-put' in the background, and the signal is not a change in the average rate but a change in the variabilitv between pulses. And so we can measure the smallest amount of that variabilitv that a fish can detect.

Now I want to give you my 'take' on how to understand what fish are doing when they are detecting sound and how they might vary among species in what they're doing. Figure 2 (bottom) shows the most primitive of ail fish; it has an otolith organ. All species have otolith organs. The otolith organ contains hair ceils with a very dense calcium-carbonate otoiith sitting over the top. Any engineer looking at this would say, that's a mass- loaded accelerometer, because if you took this whole animal and you moved it from side to side, you'd get relative motion between the hair c ells and the otolith, because of the mass, inertia, and stiffness of the connection between them. Ail those things would determine that you will get a relative motion between the otolith and the hair ceils, and that's ail that's required to stimulate the auditory system.

All fish species have otoiiths and can respond the same way to these kinds of motions. There is no reason to believe that species differ in this respect. We have determined in physiological studies, and now in a behavioral study, that these fish are extremely sensitive to particle motion. If you take a fish and simply accelerate it back and forth along a straight line, and measure the smallest amount of displacement that the animal can detect, you can still measure some kind of response with displacements as small as a 10th of a nanometer. For those of you who don't think in nanometers (10^{-9} m), a 10th of a nanometer is well below the diameter of a hydrogen atom. So these systems are extremely sensitive. Actually they're designed to detect the acceleration due to gravity, and that's a d.c. (direct current) effect. So they can respond to d.c. and to oscillations up to several hundred Hz, maybe up to 1000 Hz. All fish respond this way. If you move a fish by a couple of nanometers at a frequency between 50 and 200 Hz, the fish will respond.

So that's the generalist fish. The specialist fish (Figure 2, top), although it has the same otolith organ and acts exactly the same as a generalist, also has a swimbladder or other gas bubble that's connected to the ear by some kind of specialization. This specialist fish is sensitive not only to particle motion but also to sound pressure. Sound-pressure sensitivity comes from the fact that when you take this bubble of gas and subject it to pressure changes, the volume will change, the walls will move, the movements of those walls are transmitted to the otolith, and the otolith will move. Figure 2 (middle) shows a gray-area type of fish with a swimbladder but no known connection between it and the otolith. The question is, what does this fish respond to? The answer is pretty clear for the specialist: that at threshold, these animals are responding mostly to sound pressure until the frequency gets extremely low. We know that an animal like that shown in Figure 2 (bottom), which includes salmon, is responding to particle motion. For salmon, it has been determined that the swimbladder basically has no effect on its hearing. But for other species of fish (Figure 2, middle), we have not been very successful at showing, one way or the other, what these animals are responding to.

Now I want to talk about audiograms, and I'll just throw up all the audiograms for the fish species that have been published in the literature (Figure 3). As Art Popper pointed out, you can generally divide these into two groups: the specialists that are responding to sound pressure at threshold over most of this range, and the generalists or non-specialists that are probably responding to acoustic particle motion. The only audiograms that we should have any faith in are for the specialists, because the smallest detectable signal is specified in sound-pressure units. If these generalists (light lines) are not responding to pressure, the audiogram is meaningless. These audiograms tell us that hearing specialists can hear perhaps up to several thousand Hz, although their sensitivity is falling off quite a bit and their best hearing is perhaps from 100 to 1000 Hz. Their best thresholds are quite low, say, -60 dB with respect to 1 Pa or so. In terms of acoustic intensitv in this frequency range, this is at least as good as human hearing, sometimes better, if you take into account-the impedance of water.

The other group of audiograms that we can make some sense out of, besides the dark ones here for the hearing specialists, are the so-called particle-motion audiograms for some species that, under experimental conditions, were shown to be responding to particle motion (Figure 4, top panel). Data for the cod extend to very low frequencies. Sensitivity is shown in dB with respect to 1 μm; -60 dB here is a nanometer. What these behavioral data say is that these fish, these otolith organs, are responding down to much less than a nanometer, in a frequency range between about 100 and200 Hz, and that there may not be much species variation in this. Although these experiments haven't looked specifically at species variation, I don't believe it's going to be found. That is, otolith organs are otolith organs, and they're going to have a sensitivity that's about the same and they're not going to vary a heck of a lot.

The other panels show the same data in terms of particle velocity (middle) and particle acceleration (bottom). Kaimijn and others have argued that because the otolith organ is an accelerometer, why not look at its frequency response in terms of acceleration, the thing that actually makes it go. And when you do, although there may be some frequency selectivity or tuning here, the general picture tells you that the audiogram may be a low-pass type of function. One rule of thumb, or a general way to look at these data, is that these animals are probably doing most of their processing at frequencies ≤200 Hz.

Now I want to tell you briefly about some other things that affect the sensitivity of detecting sound or particle motion in fishes. I will begin with stimulus duration, and some of the data here are a bit controversial. Figure 5 shows data from my lab. Basically the experiment is this: We present the animal with signals of different durations and we measure the threshold at each duration. We find that as the duration of the signal becomes longer, the threshold for detecting that signal becomes lower. If the slope were 10 dB per decade, there would be some evidence that they're responding in terms of energy. They're integrating over time and power, so each of these points along this line will have equal energy. But this rule of thumb works out to ~500–1000 msec, and after that the threshold becomes independent of duration and the animal is no longer integrating power. What's interesting is that this is exactly what the auditory systems of all other vertebrates do. In this sense, these fish data are hard to discriminate from data of birds, humans, frogs, chinchillas, and monkeys. Temporal summation is a fundamental characteristic of auditory systems.

Another thing that determines the detectability of a given signal is the presence of other sound in the background that may interfere and that you might want to call 'noise'. That sound could either be something like broadband noise or it could be another tone, or it could be whatever happens to be back there. The fact is that under most real-world conditions, for us and for fish and for every other animal, the detectability of any given signal is probably determined by background noise. In other words, detectability is probably not determined by the animal's sensitivity in quiet as much as by its ability to extract signals from noise. And the effect of raising a threshold or making a signal less detectable by adding noise is called 'masking'. There are 100 years of studies on masking in humans which now have been applied to understanding masking in fish. In 1940, a physicist named Fletcher presented a way to understand the effect of noise on the detection of a tone in humans. First, he assumed that if you're detecting a pure tone, let's say it's 100 Hz, you're detecting that through some kind of detection filter or channel in your auditory system that's tuned to 100 Hz, the assumption being that vour auditory svstem is full of many of these channels, each tuned to a different frequency. And so when you detect 100 Hz, you're listening through these channels that are tuned at 100 Hz. That's when the optimum signal-to-noise ratio will occur.

Now you add broadband noise, white noise, and your threshold goes up. In other words, it's harder to detect that tone signal, and you'll have to raise its level for it now to be detected in this background of noise. So that was Fletcher's first assumption about how we detect tones. This second assumption was that this signal will reach a threshold of detectability when its power equals the power of the noise coming through this hypothetical noise filter. When the power of the signal equals the power of the noise coming through this filter, the tone is detected by the auditory system.

Applying this definition, you can use the signal-to-noise ratio or the level of the signal with respect to the level of the noise to estimate the width of this filter in Hz. And that's been done very successfully, given certain kinds of caveats, in human hearing and hearing of every other vertebrate animal that have been looked at, including fish. Figure 6 shows behavioral data from an experiment just like that. In this particular experiment, we had broadband flat spectrum noise that covered the entire hearing range, from >1000 Hz to well below 100 Hz. We simply asked, what is the required level of a signal for it to be detected, given that we have this background noise? We expressed that signal level as a signal-to-noise ratio at threshold. In other words, the level of the signal minus the spectrum level of the noise. The point at 100 Hz indicates that the signal level has to be 14 dB above the spectrum level of the noise in order to be detected. Now we measure that same quantity at different frequencies, and this beautiful function for the goldfish, and this function for the cod which resembles it, are determined. One interpretation is that there are detection filters in there. The ones centered at low frequencies are fairly narrowly tuned; they're not letting much noise through. Therefore, the detection of a tone is very efficient. As we go up in frequency, the filters are wider and wider, and so the power of the noise coming through them is greater and is causing more masking. The signal-to-noise ratio must be higher for the signal to be detected. This describes hearing for the goldfish and the cod. The effective band width predicted from all of this ranges from -20 Hz to several hundred Hz. These results from the goldfish look essentially similar to the results you would get from a human, a parakeet, a frog, and all the other animals that have been tested this way; you get the same phenomena.

There have been other experiments done in an attempt to more specifically try to measure these hypothetical filters. It's a very interesting experiment, and without going into detail, I'll just say that behavioral methods were used to try to measure the shape of these detection filters by measuring the detectability of the signals in noise. In Figure 7 we find, for every signal frequency, what looks like a filter. The filters are symmetrical; they look like band pass filters. There are data like this for other species that say, this is the way signals are detected in mammals, birds, reptiles, fish. There are no exceptions among vertebrates.

I want to mention the 'cocktail party effect', because that's one other variable that determines the detectability of a signal. The 'cocktail party effect' refers to the fact that people who are deaf in one ear tend to avoid cocktail parties. Why? Because your job at a cocktail party is to focus and listen to one conversation and to blot out all the other ones. And if you have only one ear, you can't do that. It's like recording with a tape recorder through only one microphone; all you would hear is reverberation. And this means that the human auditory system is selective, using its two ears, its ability to directionalize. It can reduce the effectiveness of a masker by paying attention to or processing only the information coming from one direction, or one sort of cone, and you can switch which cone you want to listen to.

So that experiment has been done with several species of fish, and in different situations in the lab and in the field, and you find the same thing, a 'cocktail party effect'. We had one source that was generating a noise, another source was generating a signal. When the two sources are in the same location, there's a lot of masking, this noise interferes with the detection of this signal. But if you take the noise source and put it over here, and the noise of the fish is the same amplitude as it always was, the fish's ability to detect the signal now improves by up to -15 dB, and that's really an enormous effect (Figure 8). That's a spatial filter that's been demonstrated in humans, in cats, in rats, in cod and in haddock.

Another topic is sound-intensity discrimination (Figure 9). The bottom line from the data is that the behavior of goldfish, in this case, and of humans is essentially identical. As the duration of the sounds we're trying to discriminate get longer, the threshold gets lower, and you reach an asymptote at about the same time (300-500 msec). Humans and all other vertebrates that have been looked at show nearly identical functions. In general, if you're training an animal to respond to a change in frequency, and you measure that at different frequencies throughout their range, the frequency-discrimination threshold, or this minimum detectable change, gets bigger. But it gets bigger along a general power function that looks like this (Figure 10). It's the same power function that would describe frequency discrimination in all other vertebrate animals we've looked at, including humans, except that humans are a bit more sensitive. Figure 10 shows that animals with and without specializations for sound-pressure detection may differ in terms of their ability to make frequency discriminations. That's just a suggestion from these data.

Finally I want to talk about sound-source localization. Much has been written and speculated about sound-source localization, but very few experiments have been done. Most authors and thinkers believe that the ability to determine the location of a sound source is not possible by fishes unless the otolith organs receive input directly from the particle motion. In other words, the fish has to be accelerated, and in many cases it's that acceleration vector that the animals try to determine. The animal cannot know that unless it has vectorial information, which it gets by paying attention to its hair cells on the otolith organs that are stimulated inertially. Thus, these animals must be in direct contact with the particle-motion wave form in order to determine the location of the sound source. As far as we know, if the animal is in the far-field and is detecting only pressure, like the goldfish can do, and if pressure is the only thing it can process, then it has no basis for determining where the sound source is.

I want to tell you about experiments in which animals were trained to discriminate between two sound sources that are separated in space (Figure 11). The people who did these experiments – not me – varied the separation in angle between sound sources. The bottom line is that if the signal-to-noise ratio is high enough, the fish can discriminate between sources that are between 10" and 20° apart. That's really good discrimination, They can do this in elevation, and they can do it in azimuth. They also know the difference between something in front and behind them, or something near and something far. There are about three studies here, and that's as much as we know about sound-source localization, from behavioral work at any rate.

The final thing I want to point out about this is that, even in these experiments, it's not clear that the fish know where the sound source is. The fish is sitting there restrained, and one sound comes on and then another. If the animal discriminates those two sounds as different, it responds. But just because the animal can say 'that's different from that' doesn't necessarily mean that the animal can point to where the sound source is. So while we know that animals can discriminate between different sources, if we were to train them to go to the source that is producing the sound to get a food reward, we don't know that they would do it. And so understanding the behavior of sound-source localization requires new behavioral experiments that have not been done. The literature really needs them to be done, and we would know a lot more about the sense of hearing in fish when we have those data.

Finally, these results suggest that fishes share many hearing features with other vertebrate animals. This could mean that the vertebrate sense of hearing is a general character, and suggests to me that the essential function of hearing is the same in all vertebrates. That is, hearing informs us about the physical characteristics of the sources and reflectors in the nearby environment. These characteristics appear to include their location, their azimuth, their elevation and distance, their sizes and natural vibration frequencies, and also their internal states of excitement.

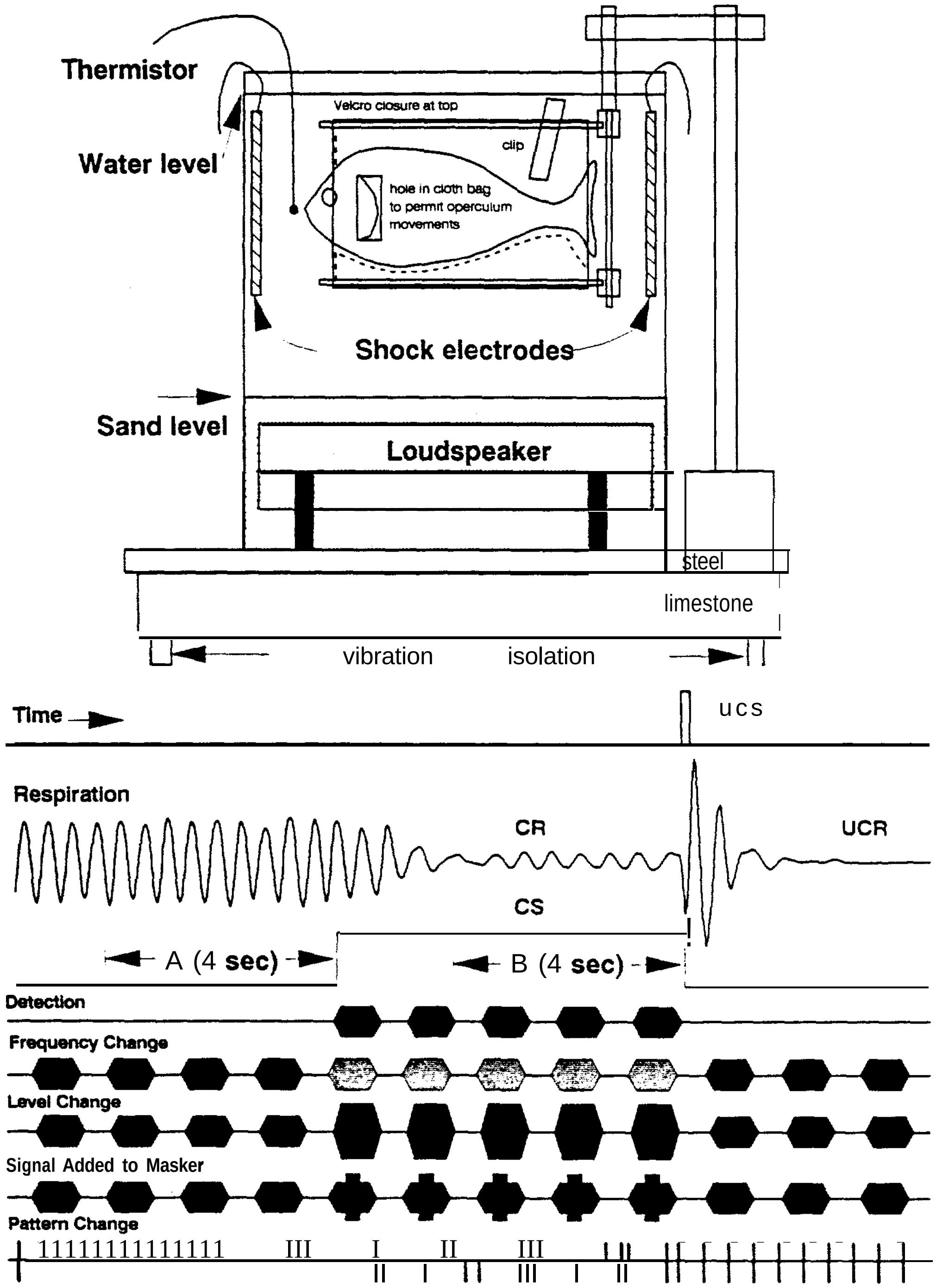


Figure 1
Experimental design for psychophysical studies of hearing in fish measuring water flow and fish respiration and heart rate.

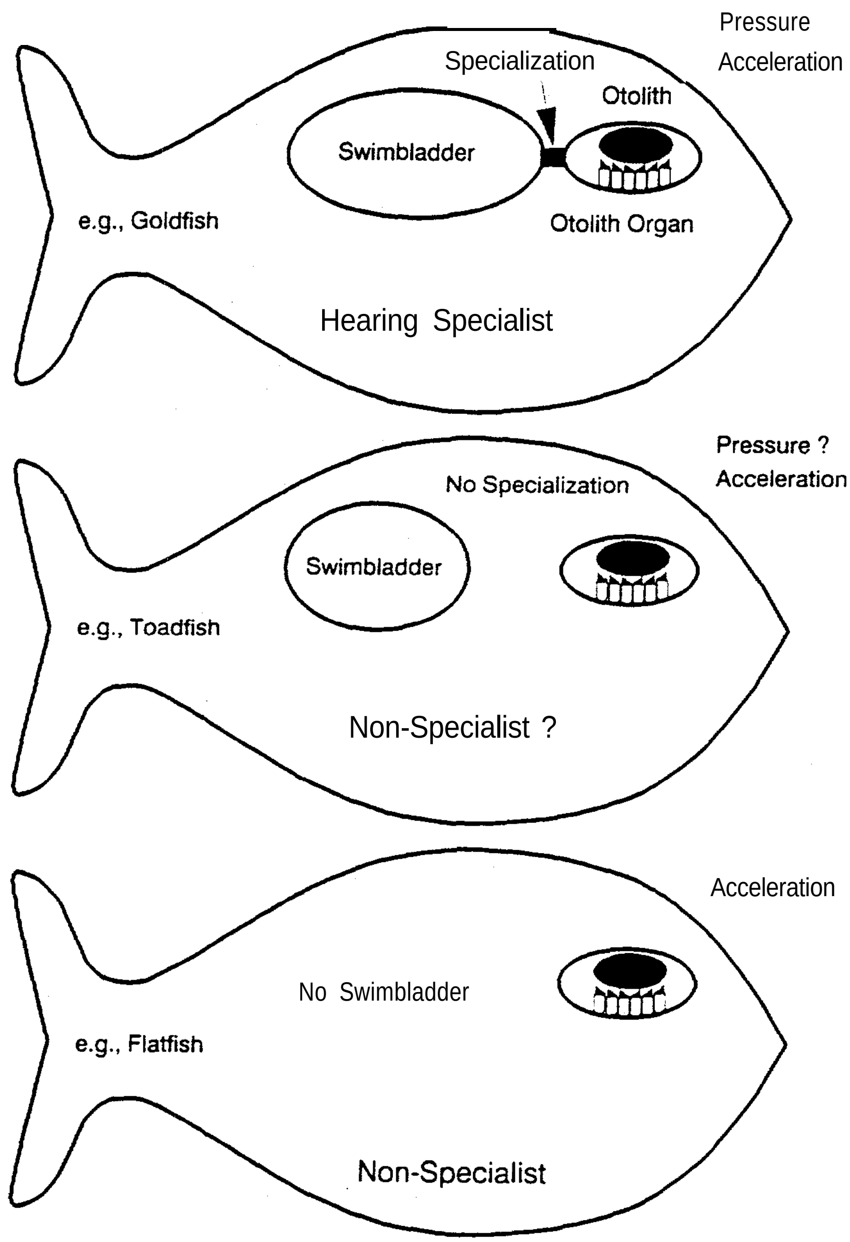


Figure 2
Functional differences between hearing specialists and non-specialists relative to the presence of a swimbladder and the sensitivity to pressure and particle motion.

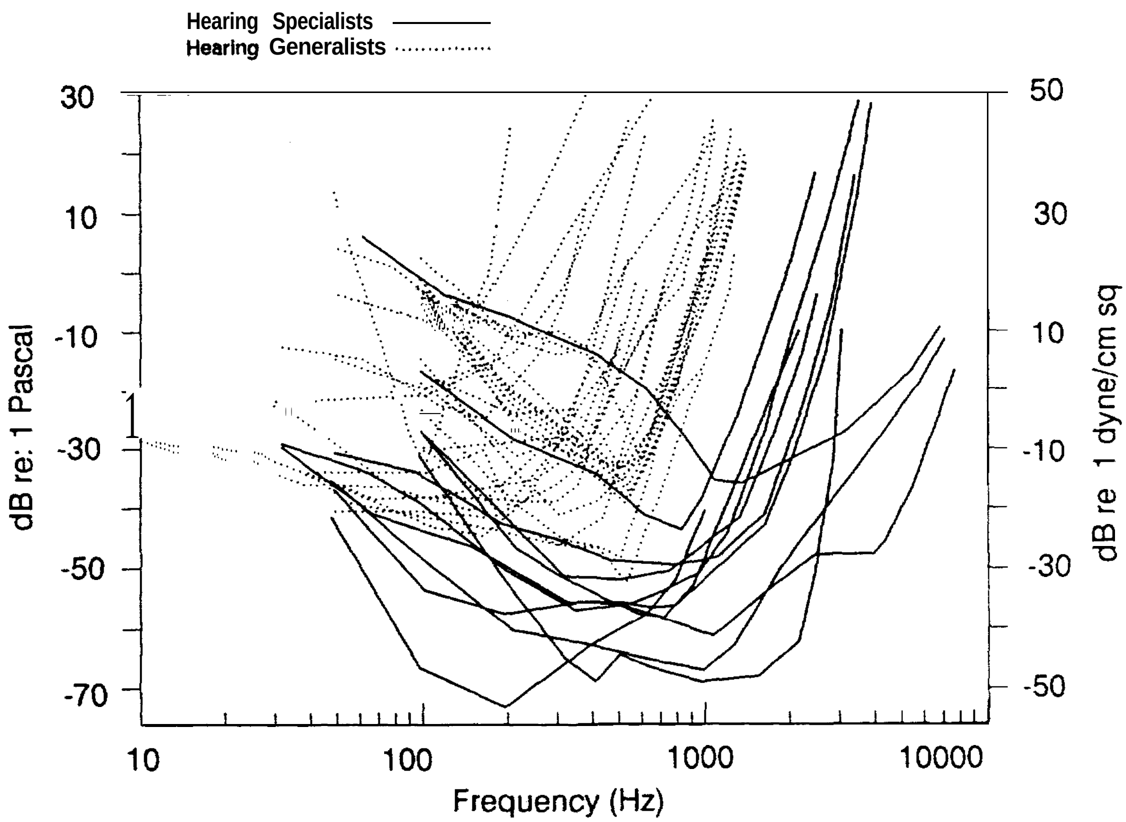


Figure 3
Audiograms for all fish species published in the literature
(Various authors; adapted from Fay 1988).

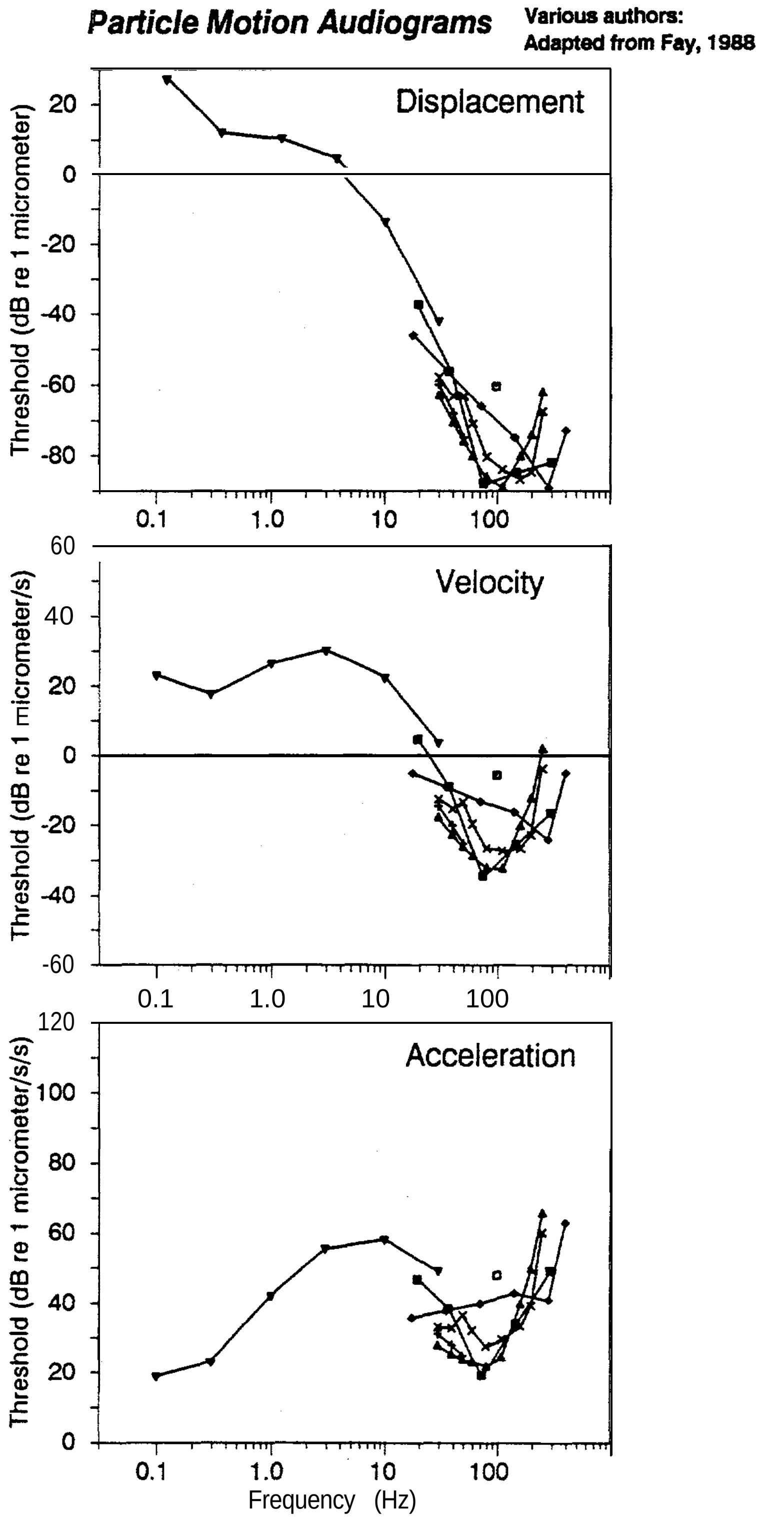


Figure 4
Particle-motion audiograms for fish species shown to respond under experimental conditions. (Various authors; adapted from Fay 1988)

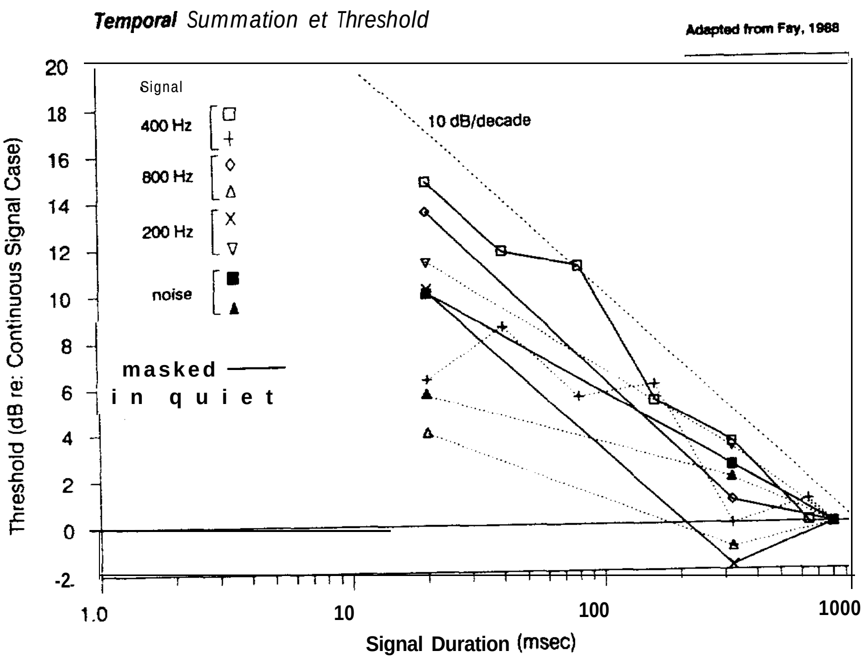


Figure 5
Data from experiments measuring thresholds for detecting sound signals of different durations. (Adapted from Fay 1988)

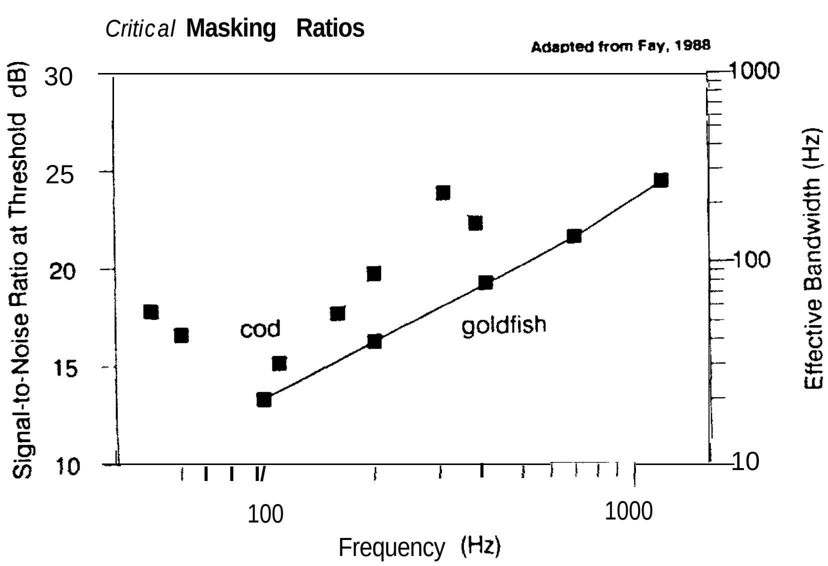


Figure 6
Critical masking ratios showing the required level of a sound signal relative to the level of background noise. (Adapted from Fay 1988)

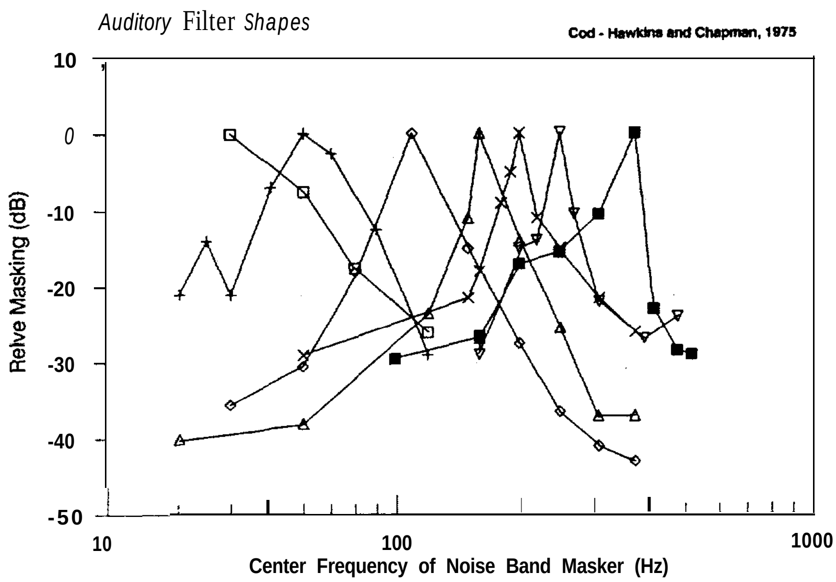


Figure 7
Auditory filter shapes derived by measuring detectability of sound signals in noise. (cod; Hawkins & Chapman 1975)

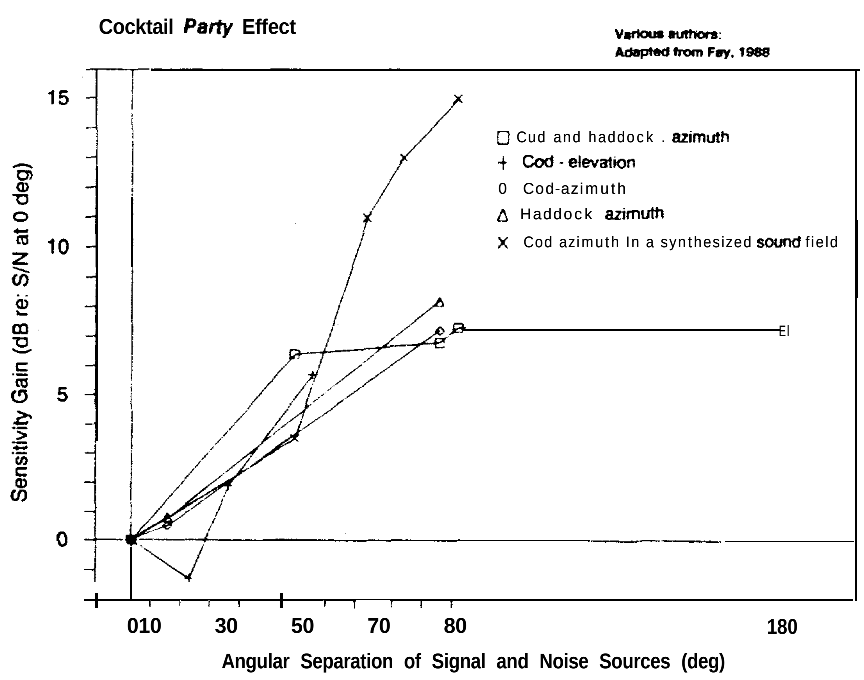


Figure 8
Spatial filter (or "cocktail party effect") demonstrated by fish in separating sound signal and noise sources. (Various authors; adapted from Fay 1988)

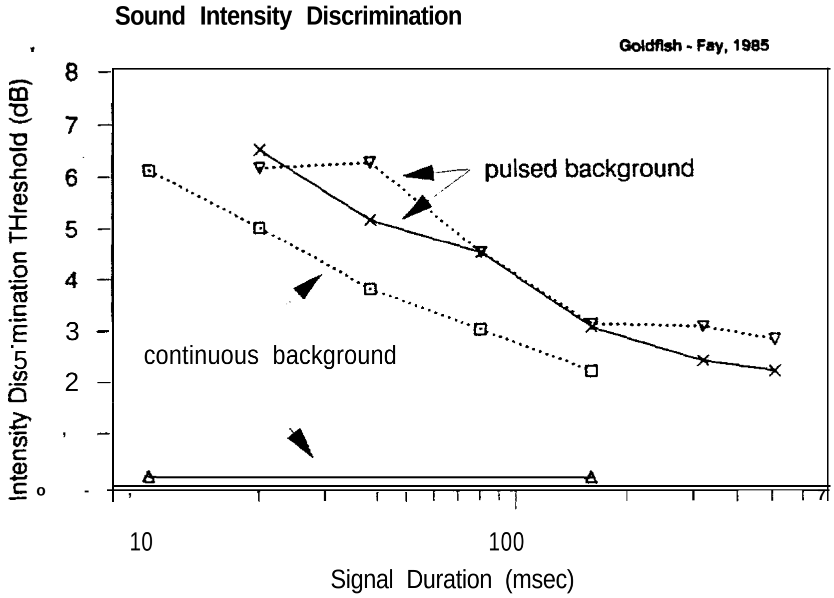


Figure 9
Sound-intensity discrimination thresholds by goldfish relative to signal duration. (Fav 1985)

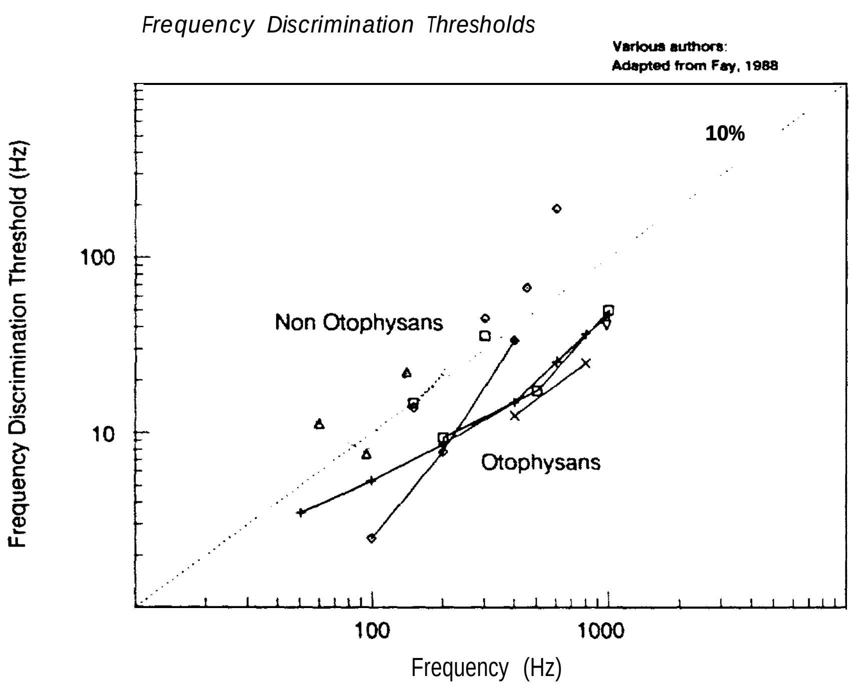


Figure 10
Frequency-discrimination thresholds by otophysans and non-otophysans. (Various authors; adapted from Fay 1988)

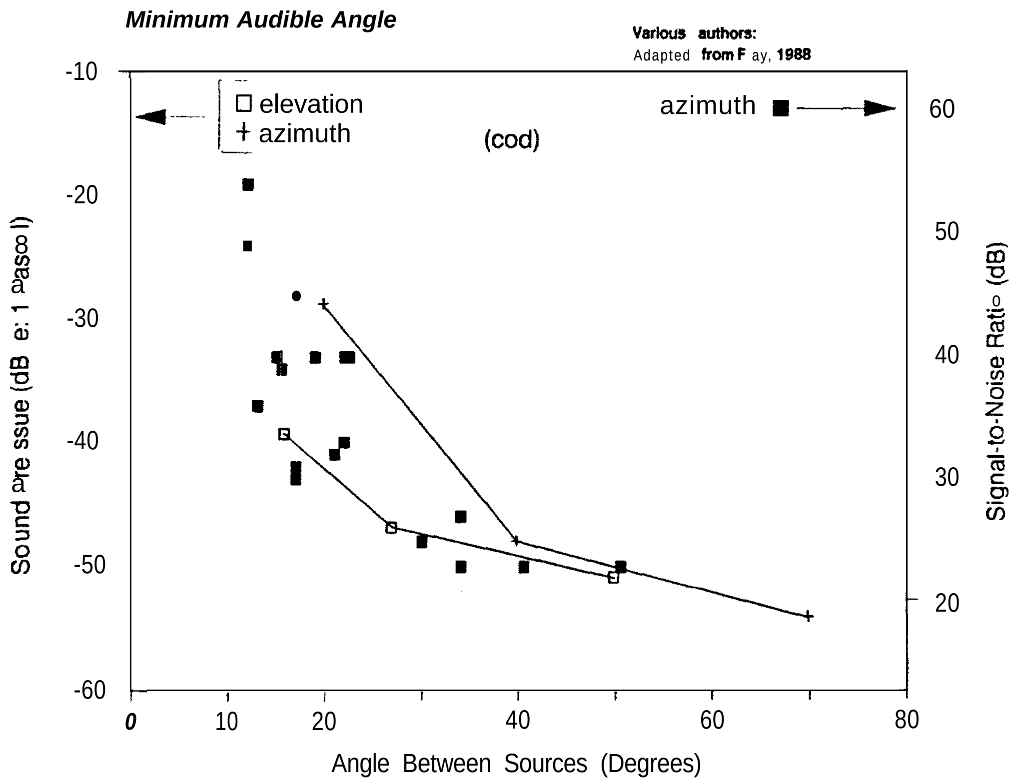


Figure 11
Minimum audible angles for discrimination by fish between sound sources.
Various authors; adapted from Fay 1988)

Infrasonic Detection by Fish

Dr. Olav Sand
University of Oslo

The main message of my talk will be that fish have an acute sensitivity to extremely low frequencies, or infrasound, even down to <1 Hz. It is also likely that infrasound is very potent in eliciting behavioral responses in fish. You have already heard that the swimbladder in fish may function as an accessory hearing organ, providing the fish with sound-pressure sensitivity, although the inner ear itself is sensitive to particle motion and not sound pressure. However, in the infrasound range the relevant stimulus parameter is particle acceleration, even in fish possessing a swimbladder. This fact has important consequences for treating and measuring such low-frequency sounds. Since we humans are sensitive to sound pressure and not particle motion, we are reluctant to accept that it is different in fish. I will therefore begin by discussing the auditory role of the swimbladder and the mechanical properties of the fish ear in some detail.

When emphasizing the auditory role of the swimbladder, it may be convenient to start with species lacking a swimbladder altogether. Plaice and dab, which are flatfish, are examples of such species. Some 20 years ago the theory was put forward that the unaided fish ear could be pressure-sensitive due to piezoelectric properties of the otolith organ itself. To test this hypothesis, Colin Chapman and I (Chapman & Sand 1974) measured the hearing thresholds in plaice and dab at two different sound-source distances. And this (Figure 1) shows the under-water set-up on the west coast of Scotland. The reason for using different sound-source distances was to change the ratio between particle motion and sound pressure. These curves (Figure 2) show the nearfield effect, orthe particle displacements as a function of sound-source distance for a constant sound pressure at different frequencies. Within the nearfield of the source, the particle motion at a constant sound pressure increases dramatically with decreasing sound-source distance. The auditory thresholds were obtained using the cardiac conditioning technique whereby the fish was trained to give a bradycardia response, or reduced heart rate, when the sound was presented. The actual threshold was then determined using the staircase method, by lowering the sound level after each positive response and increasing the level after each negative response. The threshold is defined as the level giving 50% probability of a positive response.

If the flatfish was detecting sound pressure, the sound-pressure auditory thresholds should be independent of sound-source distance. However, these audiograms (Figure 3) show that the sound-pressure thresholds were seemingly lower at a 0.7-m source distance (open symbols) compared to threshold values at a 3 -m distance. However, if the thresholds were recalculated to particle motion, there were no differences between the two sound-source distances (Figure 4). These results show beyond doubt that the unaided fish ear is sensitive to particle motion and *not* to sound pressure.

On the other hand, the presence of a gas-filled swimbladder may change this situation (Figure 5). The reason why a swimbladder may provide an auditory advantage is the much higher compressibility of gas compared to water. When a volume of gas in water is exposed to pressure variations in a sound field, it will display larger volume pulsations than a comparable volume of water. Upon exposure to sound, the surface of the bladder may thus show larger motion amplitudes than the water particles in the absence of a gas-filled bladder. These amplified motions may then be transmitted to the inner ear, providing an auditory gain to the fish.

Regarding their hearing ability, we have already seen that fish may roughly be divided into three groups, according to their utilization of the swimbladder as an accessory hearing organ (Figure 6). The 'hearing specialists' such as the otophysan species and the clupeids, here exemplified by the goldfish, have a specialized connection between the swimbladder and the inner ear. At the other extreme, we have the fish lacking a swimbladder, here exemplified by the dab. In between, we have fish possessing a swimbladder but lacking special structures linking the bladder to the ear, exemplified by the cod. In the otophysan species (Figure 7), such as the carp family and the catfish, the Weberian ossicles directly link the surface of the swimbladder to the inner ear; whereas in clupeids (Figure 8) the swimbladder extends forward as a pair of narrow tubes ending in gas-filled vesicles in close contact with the inner ear.

However, most species possessing a swimbladder lack such specialized structures (the non-specialists' or 'generalists'). Could the swimbladder function as an accessory hearing organ even in such cases? The distance between the anterior part of the swimbladder and the inner ear is usually quite short. It could be feasible that the amplified swimbladder motions are transmitted through ordinary tissue to the inner ear efficiently enough to provide an auditory gain.

More than 20 years ago, Per Enger and I (Sand & Enger 1973) studied this possibility in the non-specialist Atlantic cod (Figure 9). We directly recorded electrical activitv from the sacculus in anesthetized fish. By diving down and emptying the swimbladder through a hypodermic needle, we could compare the auditory response with different gas content in the bladder. These recordings (Figure 10) show how the so-called microphonic potentials, or extracellular receptor potentials, of the ear were drastically reduced at 300 Hz by emptying the bladder. These audiograms (Figure 11) show how emptying the swimbladder both reduced the hearing sensitivity and restricted the hearing range towards higher frequencies in cod. In the lower-frequency range, however, the hearing sensitivity was independent of gas content. This is an important finding which I'll come back to later.

Even in the eel, which has an exceptionally long distance between the bladder and the ear, we have shown (Jerkø et al. 1989) that the swimbladder provides an auditory gain in the upper part of the audiogram (Figure 12). We have seen that flatfish, which lack a swimbladder, have both poorer hearing sensitivity and a more restricted hearing range than cod (Figure 6). Could it be possible then to transform a flatfish to a cod, auditorially speaking, by providing the flatfish with an artificial swimbladder? In the flatfish experiments conducted with Colin Chapman, we studied this by comparing audiograms of dab before and after placing a small, gas-filled rubber balloon close to the head (Figure 13). Certainly this treatment both improved the hearing sensitivity and extened the audible frequency range.

We have already seen that although the swimbladder may provide an auditory gain, this gain is frequency-dependent. For instance, the cod audiograms (Figure 11) for different gas content in the bladder showed o difference below a certain frequency. This is easily explained by comparing the free-field water-particle displacements at constant sound pressure and different frequencies with the pulsation amplitude of a gas-filled bladder (Sand & Hawkins 1973) (Figure 14). You see that the swimbladder pulsations exceed the free-field pulsations only above a certain frequency, which in practice will depend on both swimbladder volume and depth. An important conclusion from this is that hearing sensitivity in the really low-frequency range is independent of the swimbladder, and for such low frequencies the fish is insensitive to sound pressure.

This was a long introduction to my main theme, namely infrasound detection in fish. Our interest in this topic was triggered by the work of Kreithen & Quine (1979) on infrasound detection in pigeons, suggesting that pigeons use their acute infrasound sensitivity for orientation and navigation. The possibility that fish utilize the infrasound pattern in their environment is particularly intriguing, because the ambient noise in the ocean continuously increases toward lower frequencies. The spectral slope is particularly steep in the infrasound range <10 Hz and even <1 Hz. Among the suggested sources of this high level of ambient infrasound in the ocean are turbulence in the transition layers between ocean currents and more slowly moving water and seismic motion of the ocean floor. Due to continental drift, there are areas of the sea floor with particularly high seismic activity, e.g., the mid-oceanic ridges. This low-frequency noise propagates long distances with little energy loss, being reflected from the continents and causing a directional pattern of infrasound in the sea.

We have shown that fish may detect this ambient infrasound, but we have no evidence that this ability is used for orientation purposes. This idea is still only a speculative hypothesis; nevertheless, it initiated our experiments on infrasound detection in fish.

To understand important aspects of this topic, we need to look more closely at the mechanical properties of the otolith organs. The transduction process is apparently common in vertebrate hair cells. However, the apical hair bundles are coupled to accessory structures, like an otolith, a cupula, or a tectorial membrane. It is the combined physical properties of these structures and the hair cells that determine the adequate stimulus, sensitivity, and frequency range of the organ. The hair cells are directionally-sensitive displacement detectors (Figure 15). The receptor current is is directly dependent on the hair-bundle displacement. This relation is very steep, with -90% of the response range corresponding to a bundle movement of only -1" or -100 nanometers (nm). Within this normal working range below saturation, the hair cells are linear displacement detectors.

The otolith organs in fish may be treated as second-order mechanical systems, or simple harmonic oscillators, as outlined by deVries (1950). In this model of the otolith organ (Figure 16A), *m* is the otolith mass, *x* is the displacement of the otolith relative to the hair cells, *k* is the elastic or spring force per unit of displacement, *d* is the damping force or frictional force per unit of velocity, and *A* is the peak acceleration of the fish. Otolith organs are nearly critically damped; and at frequences below the natural frequency of the system, the deflection of the otolith relative to the hair-cell bundle follows the acceleration of the fish. Such a system is thus an accelerometer, and Figure 16B shows the response of the model for a given acceleration as a function of frequency. The model indicates a working range of otolith organs reaching from d.c. to the upper-frequency limit of hearing.

Fish audiograms have traditionally been related to sound pressure, but this has led to misinterpretations concerning optimal frequency ranges and hearing capabilities, because the shape of the audiogram greatly depends on the acoustic parameter to which the thresholds are related.

Figure 17 shows a hypothetical fish audiogram related to particle displacement, sound pressure, or particle acceleration. When thresholds are related to particle acceleration, which is the relevant stimulus parameter at very low frequencies, the apparent drop in sensitivity towards low frequencies disappears. Figure 18 compares displacement and accleration audiograms for three different species, and the latter set of audiograms clearly shows no lower frequency cut-off. However, until fairly recently there were no experimental data supporting the existence of infrasound sensitivity in fish. The reason for this was probably of a technical nature, because for a sound source pulsating with a constant volume change, the transmitted power is proportional to the fourth power of frequency. Commercially available sound sources could not produce the large volume changes required to be efficient infrasound transducers.

To overcome this problem, we have tested infrasound sensitivity in fish using an acoustic tube (Figure 19). The fish is positioned centrally in the tube, and the whole water mass in the tube, including the fish, is accelerated by vibrators operating 180” out of phase and connected to rubber membranes at each end. Alternatively, the fish is enclosed in a water-filled chamber suspended by four steel strings, and the entire chamber, including the water and fish, is vibrated back and forth (Figure 20). Both of these methods simulate infrasound stimulation in the field.

However, to create infrasound under field conditions is quite a different task which we have solved in a different way, and Frank Knudsen will talk about that later. The first species we tested was the Atlantic cod using the familiar cardiac conditioning technique. Figure 21 shows positive bradycardia responses, i.e., reduced heart rate, to both a l-Hz and a O.l-Hz tone. The lowest thresholds we obtained in cod were $\sim 10^{-5}/s^2$ at 0.1 Hz, which is close to the previously obtained thresholds in the optimal frequency range. This represents a sensitivity to linear acceleration which is -10,000 times higher than in humans. I conducted these initial experiments with Hans Erik Karlsen (Sand & Karlsen 1986) who later also tested the plaice and perch (Karlsen 1992a,b). Figure 22 compares the infrasound thresholds of plaice with the previously known audiogram for this species. The added threshold values extended the audiogram by 8 octaves. The reason for the elevated thresholds at 1 and 3 Hz might be masking, possibly due to respiratory movements.

We strongly believe that this infrasound sensitivity of fish is dependent on the otolith organs and not on the lateral line. The mass of the lateral-line cupulae is close to that of the surrounding water, and no relative movements deflecting the sensory hair bundles will occur when the fish and the surrounding water is accelerated in a sound field. This was confirmed in experiments in which the lateral-line organs in perch were blocked by cobalt ions in the external water (Karlsen 1992a) (Figure 23). Both cobalt and several other heavy-metal ions reversibly inhibit the mechanosensitivity of the hair cells (Sand 1975, Karlsen & Sand 1987). The lateral-line hair cells are exposed to the medium and thus are efficiently blocked by cobalt, whereas the enclosed hair cells of the otolith organs are not impaired bv cobalt ions in the external water. The infrasound thresholds in perch were not affected by blocking the lateral line, thus supporting the conclusion that the otolith organs, and not the lateral line, are involved in infrasound sensitivity.

Regarding possible functional roles of this acute infrasonic sense in fish, I have already mentioned the speculative hypothesis of fish using ambient infrasound patterns for orientation purposes. Another equally speculative hypothesis is the possible use of the high sensitivity to linear acceleration for inertial navigation. This method is based on accurate measurements of acceleration, followed by integrations with respect to time to obtain velocity and distance. The remarkable ability of ballistic missiles to hit predescribed targets is dependent on inertial guidance. Although it seems unlikely that fish should depend on inertial guidance for long periods of time, such navigation could be an important mechanism during shorter periods when adequate external information is lacking.

Figure 24 illustrates another interesting possibility, based on recordings made by Kalmijn (1988). He measured the hydrodynamic noise produced by a swimming fish. The left panel shows the actual recording, and the other curves show the frequency distribution of the displacement and acceleration. It is clear that the acceleration components produced by a swimming fish are in the infrasound range. Infrasound sensitivity in fish could be important in prey-predator interactions. An approaching predator creates local infrasound stimuli, and detection of this by the potential prey would be of great survival value. It is thus not unlikely that infrasound may be particularly effective in evoking flight reactions in juvenile fish. We have tested this idea on juvenile Atlantic salmon, and Frank Knudsen will talk about these experiments later.

To summarize, the otolith organs are inherently sensitive to particle acceleration and not to sound pressure. The swimbladder may function as a transformer of sound-pressure to particle-motion, thus making the fish sensitive to sound pressure. The swimbladder provides only an auditory gain above a certain frequency range, making the fish insensitive to sound pressure in the infrasound range. This has important consequences for how we should treat and measure these low-frequency sounds. Presented as acceleration thresholds, fish audiograms have no lower frequency limit and extend into the infrasound range.

Figure 1
Sketch of the underwater apparatus and block diagram of the instrumentation system (Chapman & Sand 1974).

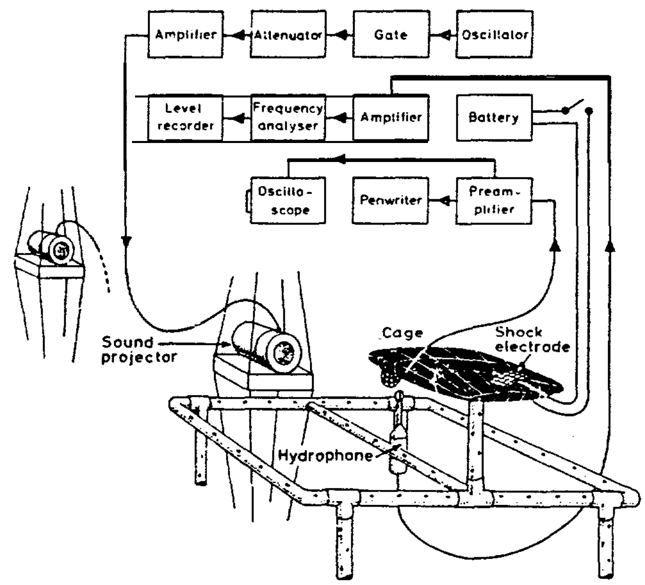


Figure 2
Particle displacement as a function of sound-source distance for different frequencies (as marked for each curve) at a sound pressure of 1μBar Chapman & Hawkins 1973).

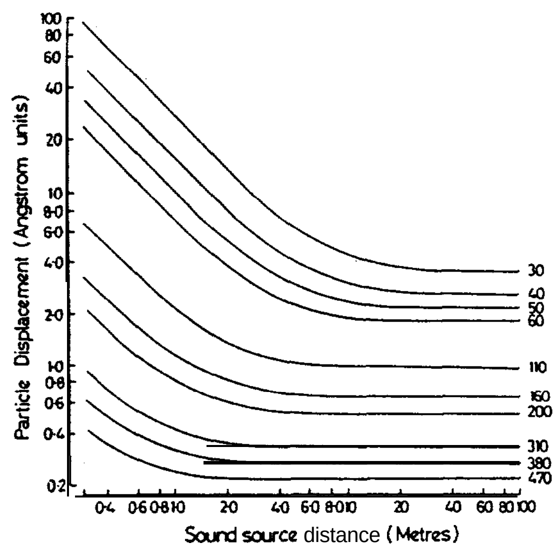


Figure 3
Threshold data for one plaice (a) andtwo dabs (b and c) in terms of sound pressure. Values for two sound-source distances are plotted separately: (0) 0.7m; (•) 3.0m
(Chapman & Sand 1974).

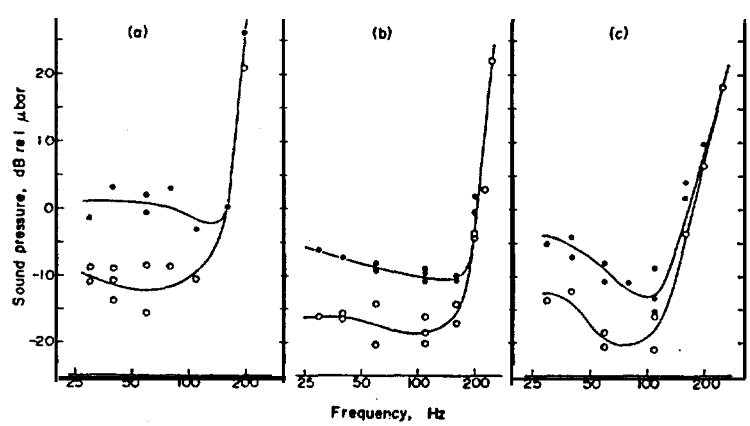
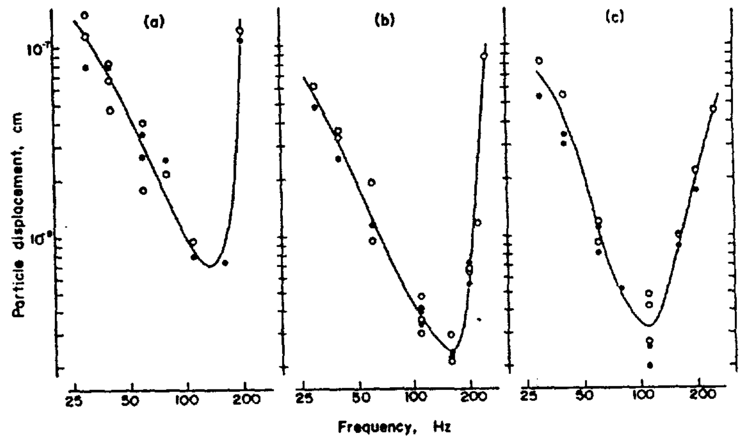


Figure 4
Threshold data in terms of particle displacement for the three fish presented in Fig. 3. Symbols for the two sound-source distances are the same as in Fig. 3. Note that the displacement thresholds are independent of sound-source distance (Chapman & Sand 1974).



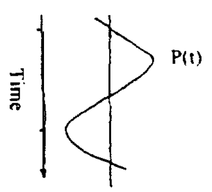


Figure 5
Particle motions radiating from a swimbladder in a sound field.

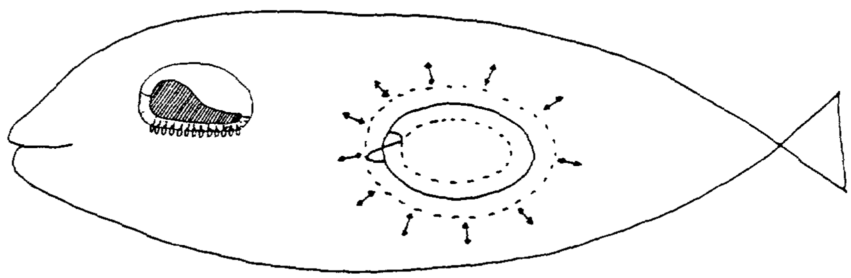


Figure 6
Audiograms of selected species of fish compared with the human audiogram.

Figure 7
Weberian ossicles in the otophysan species.

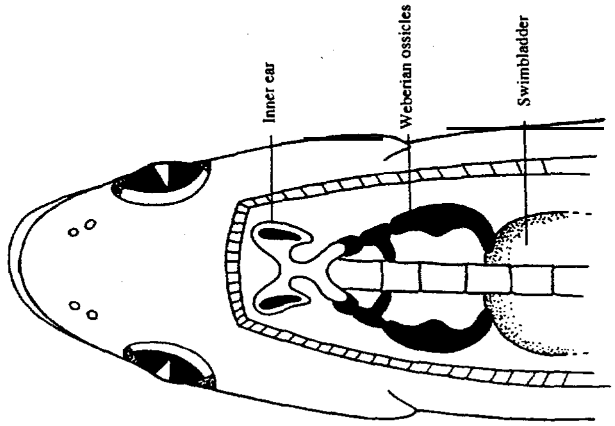


Figure 8
Anterior extension of the swimbladder in the clupeids.

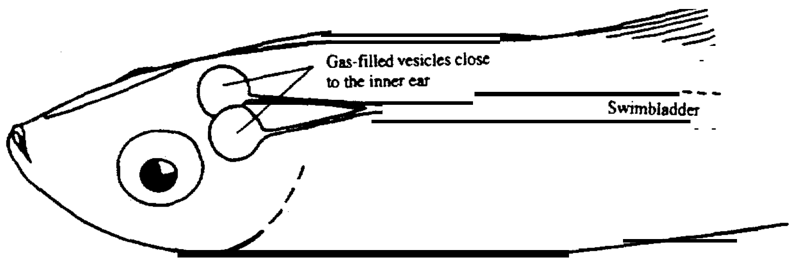
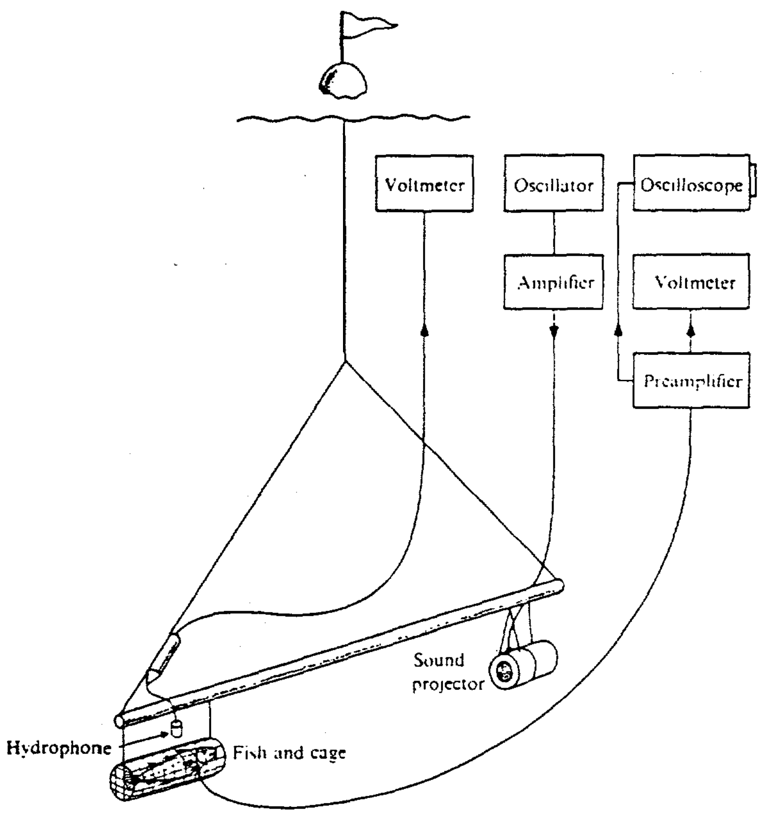


Figure 9
Sketch of the experimental arrangement for testing the effect of varying swimbladder content on the saccular microphonic potentials (Sand & Enger 1973).



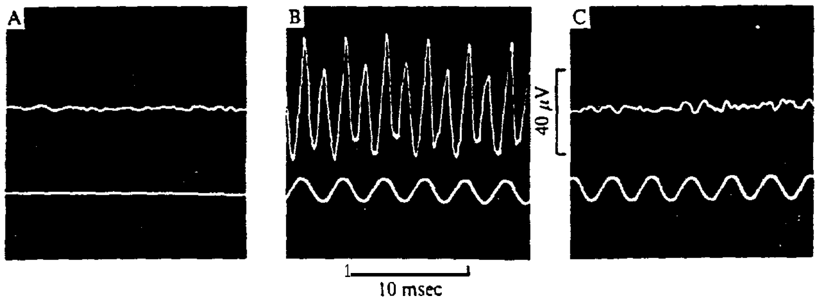
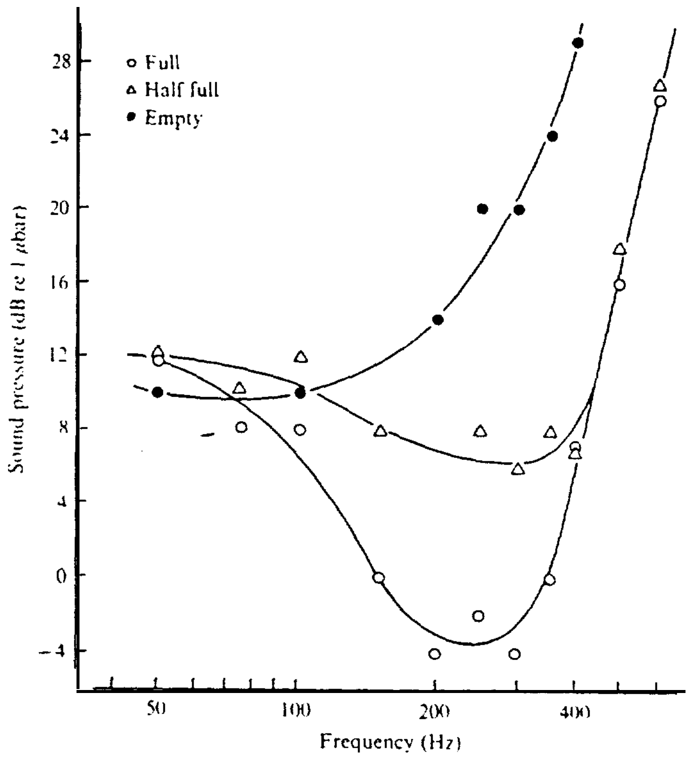


Figure 10
Oscillographic recordings of the saccular microphonic potentials (upper trace) evoked by background noise **(A)** compared to the microphonic potentials generated by a 300-Hz tone of 22 dB with **(B)** and without **(C)** gas in the swimbladder. Sound recordings on lower beam. Note the pronounced decrease in the microphonic potentials caused by emptying the bladder (Sand & Enger 1973).

Figure 11
Relative audiograms showing the sound pressure necessary to evoke microphonic potentials just above the noise level as a function of frequency. Values for three different swimbladder volumes are included. Same fish and symbols as in Fig. 3. Note that for all frequencies >100 Hz, the existence of gas in the swimbladder has a positive effect on the microphonic potentials (Sand & Enger 1973).



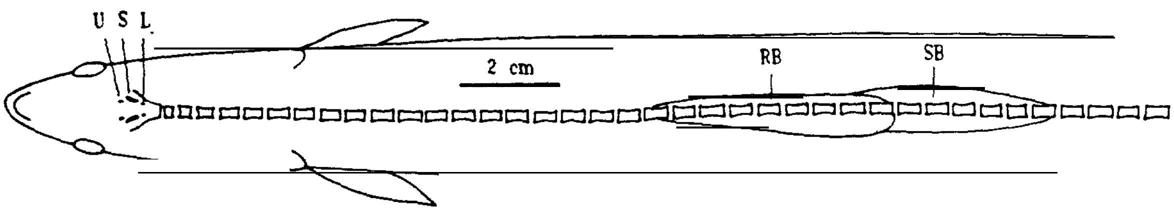
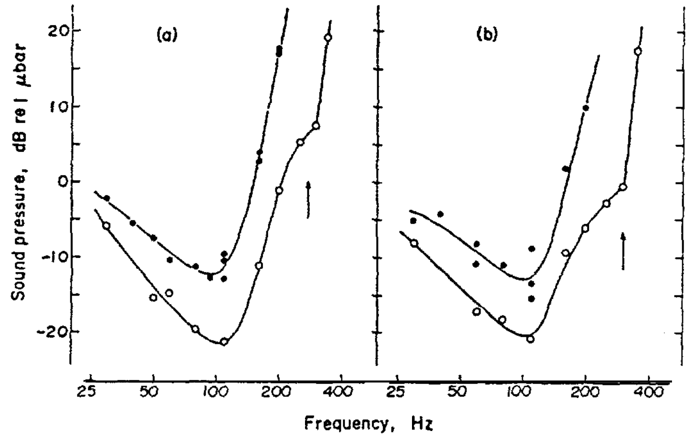


Figure 12
Position of the swim bladder (RB & SB) relative to the innerear otoliths (U,S,L)in a W-cm eel (Jerkø et al. 1989).

Figure 13
Sound pressure thresholds for two dabs at 3-m sound-source distance obtained with (o) and without (•) a small air-filled balloon beneath the head of the fish. Arrows indicate the balloon resonance frequency (Chapman & Sand 1974).



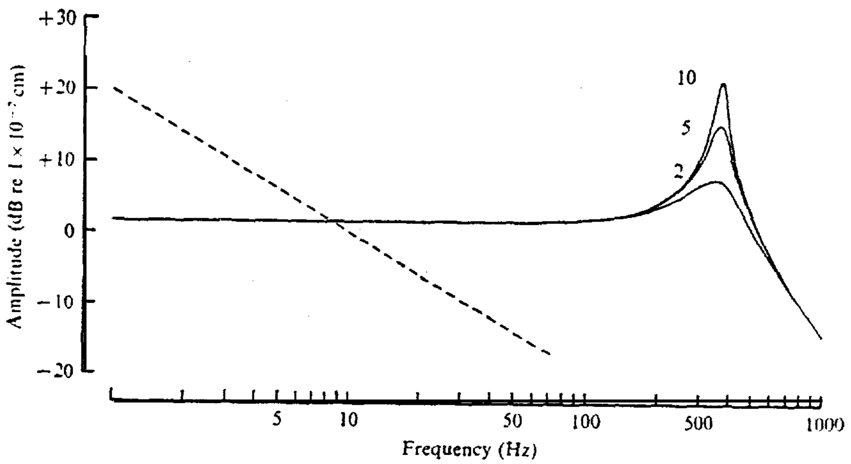


Figure 14
Curves illustrating the radial pulsation of a damped bubble (Q values of 10, 5, and 2 are indicated) in a sound field. Bubble radius is 1.5 cm and the depth 20 m. Soundpressure is kept constant at 1 dyne/cm^2. Water displace-ments accompanying this sound pressure for a propagated plane wave in the free field are shown by broken line (Sand & Hawkins 1973).

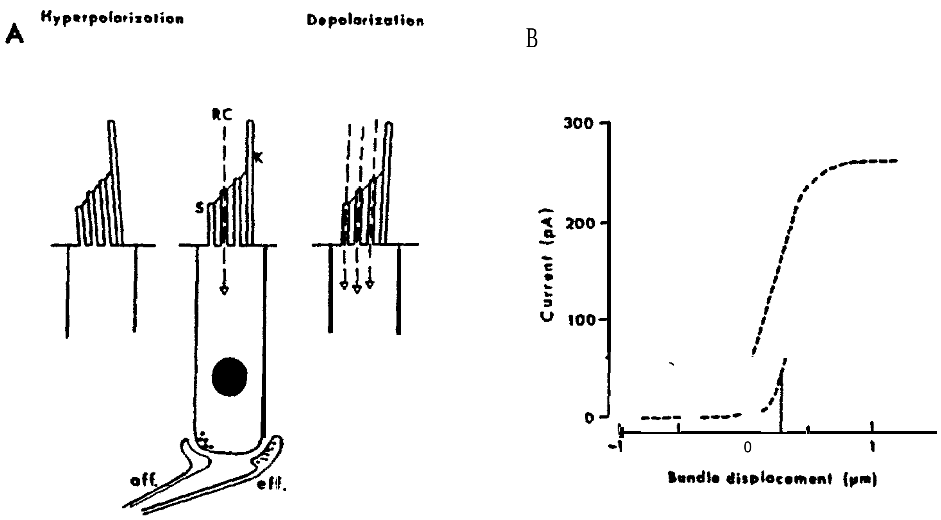


Figure 15

(A) Hair cells are directional-sensitive displacement detectors. Stereocilia (S) deflections towards the kinocilium (K) cause an increase in the receptor current (RC) and depolarization. Opposite movements of the stereocilia lead to reduced receptor current and hyperpolarization. **(B)** Receptor current in a hair cell related to hair-bundle displacement. Below saturation, hair cells may be treated as linear displacement detectors; however, in the time and frequency domain, this linearity is modified by adaptation and tuning characteristics (Karlsen unpubl.).

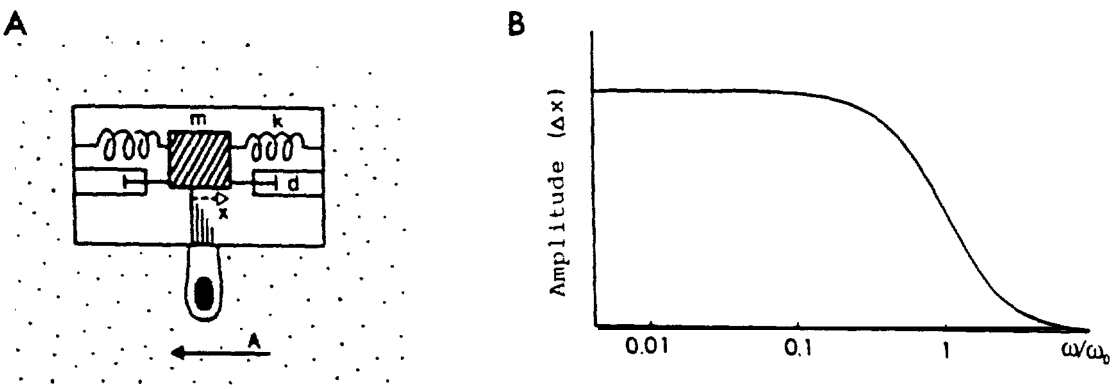


Figure 16

(A) Otolith organ treated as a simple second-order mechanical system, where m is the otolith mass, k the spring force per unit of displacement, d the frictional force per unit of velocity, x the displacement of the otolith relative to the hair cells, and A the peak acceleration of the fish. **(B)** Response of the otolith organ model for a given acceleration of the fish v. stimulus frequency (modified from Kalmijn 1989). Responses are expressed as hair-bundle displacement (linear scale); frequency is expressed as stimulus frequency ω over the natural frequency ω_0 (logarithmic scale). Otolith organs are nearly critically damped (de Vries 1950), and at low frequencies the response follows the accleration of the water volume and the fish (Karlsen unpubl.).

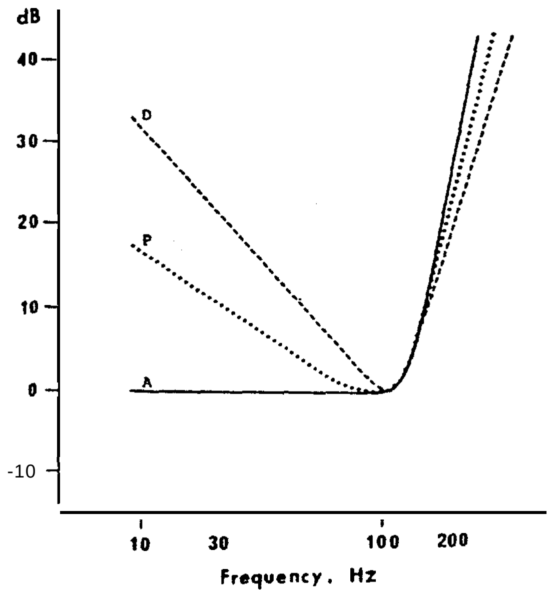


Figure 17
Hypothetical fish audiograms related to particle displacement (D), sound pressure (I'), or particle acceleration (A) (Karlsen unpubl.)

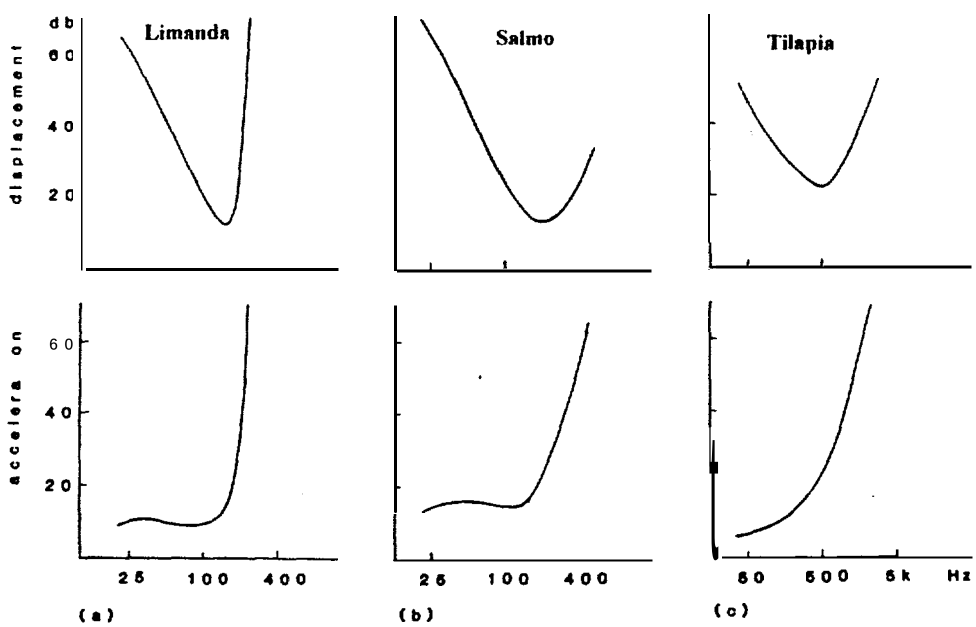


Figure 18
Displacement and accleratioin audiograms for three different species (Kalmijn 1988).

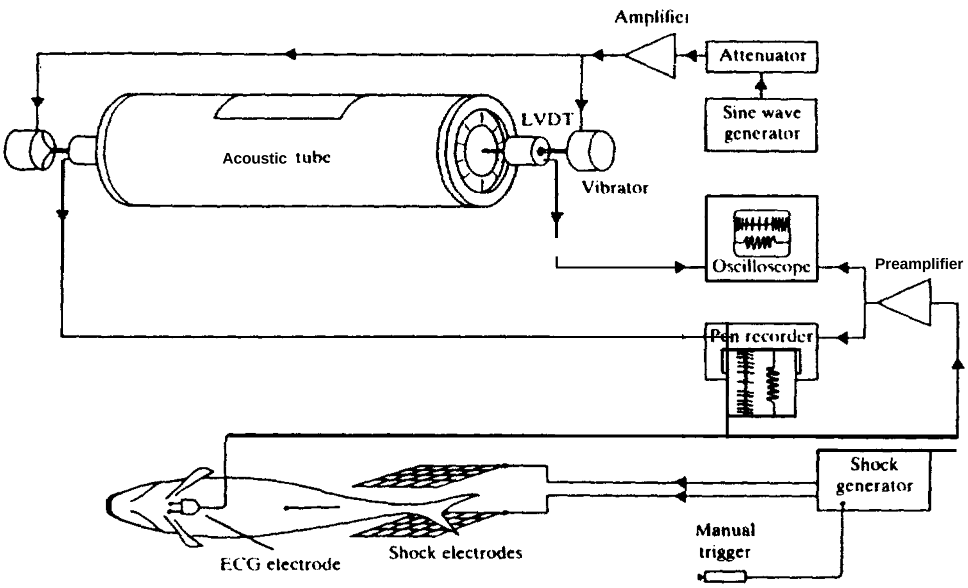


Figure 19

Experimental arrangement for testing infrasound sensitivity in cod. Fish was positioned centrally in an acoustic tube, and stimuli were delivered by oscillating the pistons at each end 180” out of phase (Sand & Karlsen 1986).

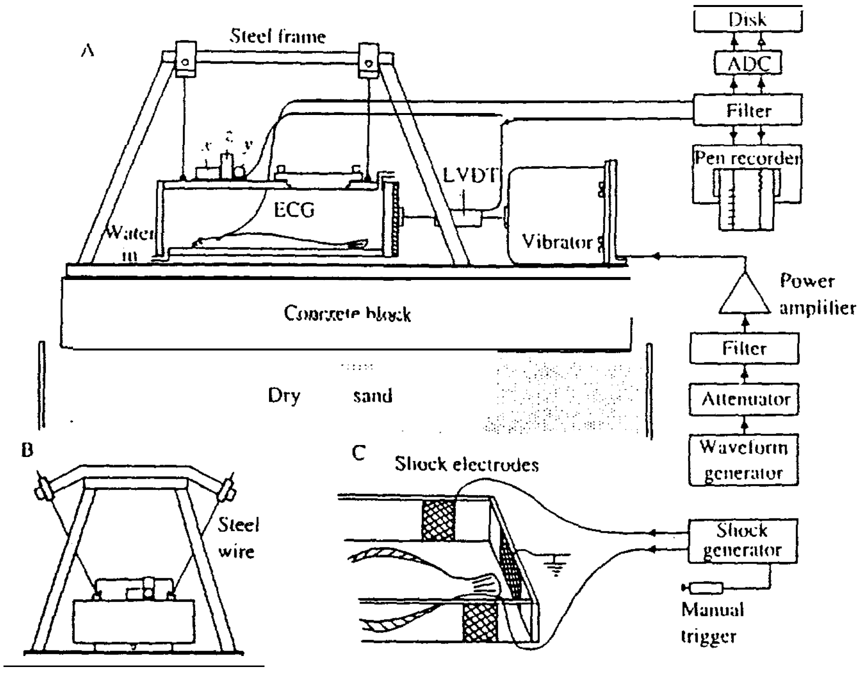


Figure 20

Experimental apparatus for examining the sensitivity of plaice to infrasound. Fish was placed in a thick-walled Perspex chamber which was slowly circulated with seawater (A). Chamber was suspended like a swing by four steel wires **(B)** and driven by a vibrator (Karlsen 1992b).

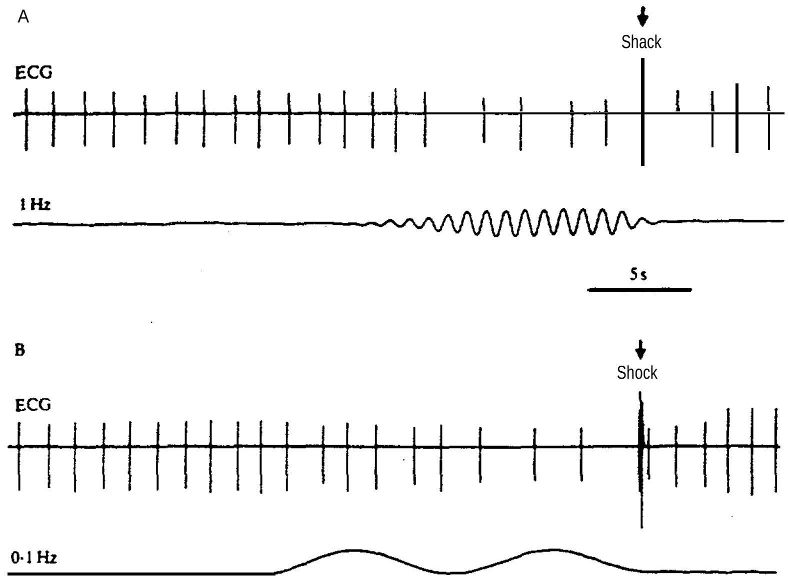


Figure 21
Conditioned cardiac response (slowing of heart rate) in cod to 1 Hz **(A)** and 0.1 Hz **(B)** infrasound. Lower trace in each example is a record of the piston displacements. An electric shock was given at the end of each stimulus (Sand & Karlsen 1986).

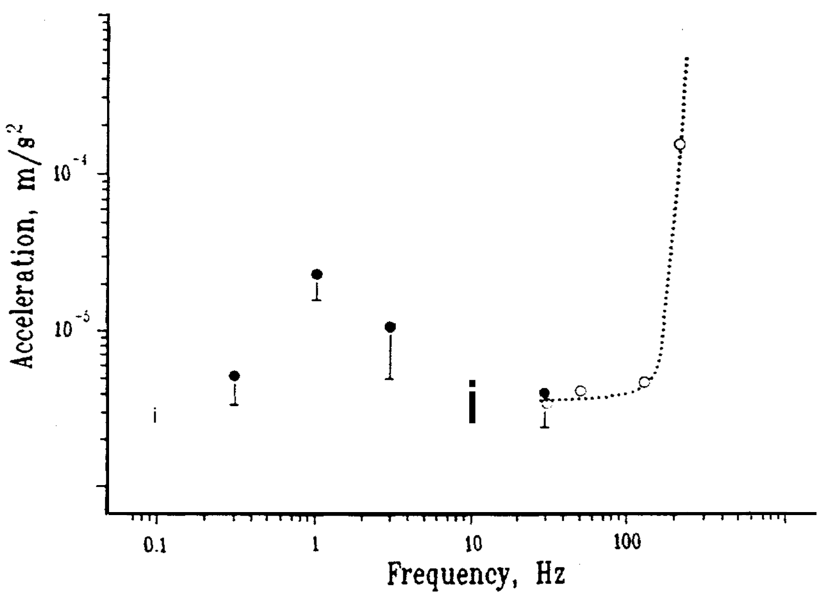


Figure 22
Auditory thresholds obtained in plaice for the frequency range 0.1–30 Hz, presented as mean values +SD. Six plaice were examined and all gave well-defined thresholds at the frequencies tested. Dotted curve gives the accleration thresholds found in plaice by Chapman & Sand (1974). (From Karlsen 1992b).

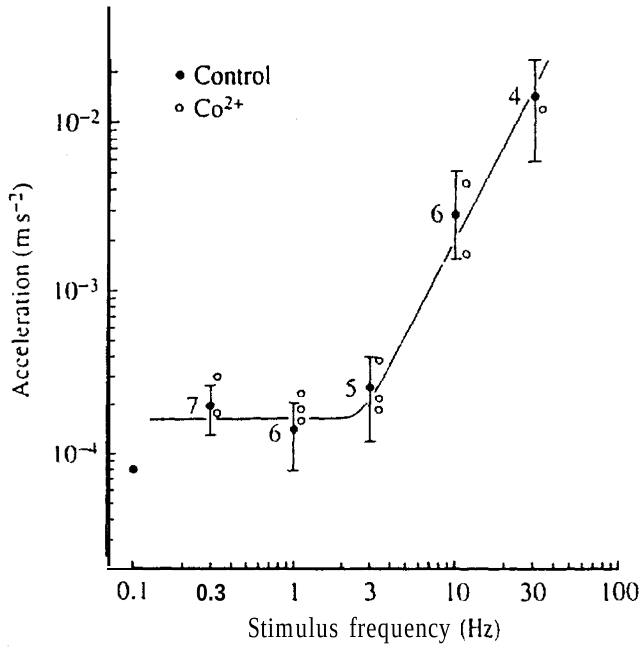


Figure 23

Acceleration thresholds (mean±SD) for control (•) and Co^{2+} treated (o) perch stimulated at different frequencies. Numbers of thresholds obtained at each frequency for control fish are indicated. Each (o) represents an individual threshold (Karlsen 1992a).

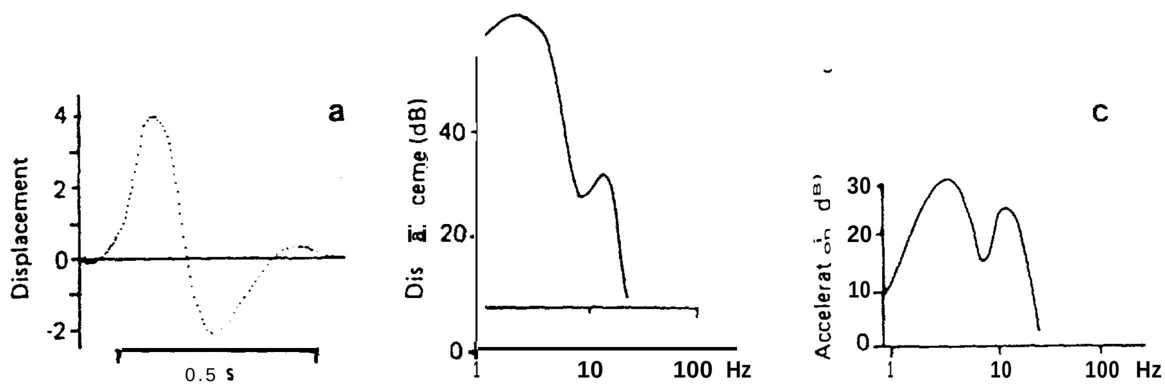


Figure 24

Flow field of an approaching and passing goldfish. (a) Original displacement recording, **(b)** displacement amplitude spectrum, **(c)** acceleration amplitude spectrum. Relative units (redrawn from Kalmijn 1988).

Summary of Fish Bioacoustics

Dr. Arthur N. Popper
University of Maryland at College Park

In a recent review, we (Popper & Fay 1993) looked at what we thought were the critical questions that needed to be asked over the next five or ten years with regard to fish bioacoustics. I went back and looked at the paper to see how many of the issues we brought up then might be germane to this conference. I am going to end this session by pointing out some of the issues, without discussing them in any length.

- What sounds do fish listen to? Are they listening only to sounds that cause specific behaviors such as those David Mann talked about, or are they listening to the environment to get a general sense of the auditory scene? Until we know what fish are listening to, we won't know whether the sounds we put into the water might be playing havoc with fish behavior.

- What is the hearing bandwidth of different species? Dick Fay has shown you an audiogram of 75 fish species, and you saw the variability (see Fay 1988). Is that variation of behavioral significance? And how do we use that information in designing various acoustic mechanisms to control or affect fish? Dick Fay brought up the very important issues of hearing in the presence of noise and of masking. If you're presenting a sound to control the fish, and there is a tremendous amount of background or masking noise, is the control sound going to be effective? Clearly, understanding the sounds in the environment before designing a stimulus is a very important thing to think about.

- One of the issues that Dick Fay mentioned briefly is that of sound localization. How well do fish tell where sound is coming from? This is a very important role of the auditory system in all vertebrates, and it is reasonable to expect that fishes would have evolved mechanism?; to determine the position of predators or prey (Popper & Fay 1993). Dick commented that fish can discriminate sounds that are 20-30" apart. The fact is that we have very little data, and this is technically a very difficult question to ask in water (see discussion in Popper & Fay 1993). You need to work in large, open areas and these studies are not very conducive to work in tanks (but see Lu et al. 1996). Still, we need these kinds of data to understand whether fish know where a sound is coming from. If a fish cannot discriminate the position, it cannot reliably swim away. Thus, sound localization becomes a very relevant issue for fish passage.

- We have not mentioned the Mauthner cell. This is a large cell found in the brainstem of many species of fish that is involved in what is called the 'startle response' (see Eaton & Popper 1995, Popper & Edds-Walton 1995). The startle response helps orient fish away from a sound that has a sudden onset, and may be involved in sound-source localization and avoidance of predators.

- There are important questions about age-related changes in the hearing ability of fish. What is the significance of adding sensory hair cells (see Popper & Hoxter 1984, Lombarte & Popper 1994)? If fishes hear differently as they get older, or if the ear changes with age, it is possible that adult salmon, 2-year-old fish, and smolts may not hear the same things. We have no data on growth and changes in the ear of salmonids, of clupeids, or any of the fish we have discussed today. However, this may ultimately wind up being a critical question if we find that sound is useful in control of fish behavior.

- A relatively new question deals with how clupeids and cods detect ultrasonic signals (see Nestler et al. 1992, Astrup & Mhl 1993). Virtually nothing is known about how these sounds are detected, nor do we know much about the range of detectable sounds.

- Mardi Hastings and I have been working on the effects of intense sounds on the octavolateralis system (e.g., Hastings et al. 1996). How long do the effects last? Can the hair cells regenerate? These and related questions are of considerable importance if we are to continue to use sounds to control fish behavior, since long-term exposure to sounds of even moderate intensity can result in damage to sensory cells involved in sound detection. This, in turn, may have deleterious affects on the ability of fishes to survive, both short-term and long-term.

- Finally, we need to consider whether data from one species can be extrapolated to another. While data are available on hearing abilities and structure of the octavolateralis system in only a small portion of the more than 25,000 extant species of fish, even this limited sample suggests significant inter-specific variation in function and hearing capabilities (e.g., Popper & Platt 1993). Thus, great caution must be taken in extrapolation, especially when considering species of different higher taxa, and perhaps even species of different genera.

Question and Answer Session

MR. JOHNSON: I'm Peter Johnson with the Waterways Experiment Station, and I have a question for Dr. Sand. You had a slide up there with two panels, a sound-pressure function on the left with two different critical lines. And I think I heard you say that if you convert those values to particle motion or particle acceleration, you get a nice straight line. I'm wondering if you could comment on that conversion. 1 didn't think that was valid.

DR. SAND: These experiments were done in the ocean, far from any reflecting surfaces, so we could use ordinary wave variations to recalculate from sound pressure back to particle motion. And when we did this, the threshold values expressed as particle motion showed no difference with sound-source distance, as opposed to the sound-pressure threshold values. This really showed that the relevant stimulus was particle motion. In that particular slide, the particle motion was expressed as displacement, but it doesn't matter. You can express it either as acceleration, displacement, or velocity.

MR. GIORGI: I'm Al Giorgi with Don Chapman Consultants, and I have a question for Dick Fay. You seem to imply that the 'cocktail party effect' would be associated not only with the non-specialist but the specialist as well. Is that correct?

DR. FAY: It's a phenomenon that would be associated with any fish that can hear directionally. But in order to hear directionally, or in order for that phenomenon to occur as part of directional hearing, that fish's ear has to be responding directly to particle motion. That could happen with hearing specialists or non-specialists alike. In other words, all fish ears respond to particle acceleration, although specialists also respond to something else – sound pressure.

DR. BROWN: I have a question for Olav Sand. I was really intrigued by your addition of the little balloon to the flatfish that didn't have a swimbladder. Was that kind of experiment ever done to examine directional hearing?

DR. SAND: No, not really. Certainly the radiated pulsations from the balloon would have a radial direction, independent of the direction of the incident sound. I'm not sure what you are hinting at, but for those fish that possess a swimbladder and are able to detect direction, it's a major task to separate these two inputs: the direct input, which could be very small in the farfield; and a very large input from the swimbladder. How can the fish separate these and distinguish a direct acceleration from an indirect acceleration? No one has really done any clarifying experiments or has suggested a good theory about how fish are able to do this task.

DR. BROWN: My suggestion is that the motion induced by the bladder may be 180° phase to the motion induced by the water. Which means that at low frequencies, where the vector is slightly different between the right and left ear, the swimbladder may remove the common mode and yield a very large phase difference.

DR. SAND: Yes, it could be, if the fish is a specialist for phase analysis. Several experiments have shown that.

MR. BROWN: I'm Ron Brown with Flash Technology, and I have a question for Art Popper. Does the rapid acceleration of the number of cell hairs as the fish gets older indicate that older fish can potentially hear better than younger fish?

DR. POPPER: That's one of the possibilities. Our guess is that it's not the case, based upon no data, so I'm not restrained here. Would it be logical, for instance, for you and your kids to hear different sounds? You might want it to be the case, so you didn't have to hear them. But it's not something we would do biologically, because you want to hear the same thing. So my guess is that the fish are hearing the same things. But as I said earlier, our guess is that as the fish grows, the swimbladder position clianges relative to the head, since the ear changes relative to the cranium, and that you are compensating for changing in size. So you are dealing with the fact that the fish grows by adding hair cells, so the fish always hears the same amount, the same information.

DR. HASTINGS: You made the comment that it's known that a juvenile could not detect certain prey until it grew older. And if you think of this environment as being extremely noisy, and the Columbia River system has to have a large level of ambient noise, it could be that you're just increasing the signal-to-noise ratio by adding hair cells.

DR. POPPER: That's a possibility.

DR. HASTINGS: Yes; you would get more signal, so your signal-to-noise ratio goes up, you are able to do a better detection. And that being the case, you would need different signals for juvenile fish than you would for more mature fish.

DR. POPPER: But in many cases, you're not dealing with the Columbia River, you're dealing with --

DR. HASTINGS: Ambient noise in the ocean, anyplace in the water, ambient noise is --

DR. POPPER: But at the same time, you could argue the reverse, that small fish which are prey to many more animals might want a higher signal-to-noise ratio just to be able to detect --

DR.HASTINGS: Right. 1 am just saying it's another way --

DR. POPPER: That's another way to look at it, sure. Again, we are not graced by data.

DR. SAND: Certainly, in addition to adding hair cells, you add mass to the otilith. Also the size of the swimbladder is changing as the fish grows, which has important bearings on the natural or resonance frequency of both these systems: the harmonic oscillator, which is the inner ear, and the resonance properties of the swimbladder. So I'd be surprised ii growth does not affect some aspects of hearing ability.

DR. POPPER: But the only data in the literature is from back in 1971 when 1 looked at hearing thresholds in goldfish, small vs. large, and found that the thresholds were the same. The experiment wasn't aimed at this question, but that's the only data in the literature. I wouldn't say that's the answer, Olav, but it's possible --

DR. SAND: Your thresholds were probably heavily masked.

DR. POPPER: I don't know. We could argue that another time. But the fact of the matter is that if you change the swimbladder and mask the otolith, but again by adding hair cells, you may be dealing with that, and still come out with the same thing. I don't know.

MR. BELL: Curtis Bell with Dow Neurological Sciences Institute. Both Dr. Fay and Dr. Sand had measurements of threshold for acceleration which seemed to be rather different. I wasn't sure of the units, and I wonder if you could clarify that. I also wonder how that compares with our own sensitivity to acceleration.

DR. SAND: The infrasound thresholds in fish are 10^{-5} m/sec^2, or the same threshold values found in the optimal sonic frequency range for the same species. For plaice and for perch, I showed you that the audiogram was flat from the sonic region down to 0.1 Hz, which was the lowest frequency tested. Sensitivity to linear acceleration is due to otolith organs. As you know, we have both the saccuius and the utriculus, and our sensitivity to linear acceleration there is -10,000 times less than in fish.

DR. FAY: In the picture I showed that had some accelerations, the units were dB with respect to 1 μm/sec/sec. So the decibel value would look quite different from m/sec, and so on. But the thresholds I was dealing with were really displacement thresholds, and I recalculated them in terms of acceleration. So I can tell you what those displacements are at 100 Hz. I think I mentioned it's between 0.1 and 1.0 nanometer at 100 Hz. So in terms of human sensitivity to displacement, the only comparison I can make is that at the threshold of hearing for a human at its best frequency, which is -2000 Hz, the basilar membranes are moving up and down about 1 nanometer. And so the threshold of the fish and the threshold of the human are within about the same order of magnitude at the optimal frequency for the given system.

Relating Fluid Dynamics, Acoustics, and Behavior to Designing Fish-Friendly Structures

Dr. John Nestler
U.S. Army Engineer Waterways Experiment Station

My goal in this presentation is to integrate information given by the other presenters and to build a conceptual framework that can be used to guide the development of fish-friendly structures. We have heard presentations of the physiological and anatomical details of fish hearing. Rather than starting out at nanometer scales and the scholarly details of fish hearing, I tend to start at larger scales associated with attempts to guide fish near dams. These scales may be large enough to be measured in 1000-m increments. Our team has agonized over many of the issues related to fish guidance presented here. We've tried to build fish-protection systems that integrate structural and acoustical barriers and other modalities. From that experience, it became clear to us that the key to developing fish-friendly structures is to have a systematic framework that integrates fluid dynamics, acoustics, and fish behavior. Fluid dynamics and acoustics are key variables to which most fish respond and that are highly modified from natural conditions by the operation of dams. These variables must be considered as part of any effort to design fish guidance systems.

I am going to summarize our experience and, through this summary, propose a conceptual foundation that can be used as the first step in the goal of developing fish-friendly structures. This is a slide (Figure 1) of the Missouri River, and I show it to help us consider the riverine environment from a fish's perspective. This environment is rich in acoustic and hydrodynamic stimuli. Now imagine that you are a fish living in this environment-what information would you be acquiring with your hearing system? Fish have a highly evolved hearing system, but nobody seemed, at least 5 years ago, to understand what information fish may be acquiring in freshwater, even though fish dedicate a large part of their neural mass to the collection and processing of acoustic information.

We considered this question and came up with the following concept that I will generally illustrate using some "Gedanken" (thought) experiments. Imagine a river channel sufficiently dewatered (as can be found downstream of some peaking hydropower dams) that you could walk in it. You could pose the very reasonable question: Is the distribution of features in this channel random or nonrandom? I believe the answer is that the distribution of features is nonrandom. I think most fluvial geomorphologists would also argue that they're nonrandom even though the pattern may be subtle and difficult to describe in terms of simple geometric measures. Now we can continue on with this simple thought experiment and pose another question: If we were to take a fluid medium like water and push it through this channel, could we expect the behavior of that fluid medium to respond in any way to the information content of this channel? I believe the answer to that question is also yes. We can further ask how this information (the pattern of the channel) is packaged. It is probably contained in background acoustic signals and in fine-scale and coarse-scale hydrodynamic patterns. Not surprisingly, the fish sensory system is beautifully evolved to collect information packaged in this way.

So, from my perspective, starting at a macroscale, the fish's challenge is to acquire information about its environment. It needs this information to navigate through a world in which vision is oftentimes not a useful sense (during the night or in turbid water). Fish, in general terms, have the sensory system needed to extract information about its fluid and structural environment without relying on vision. This is very relevant, because when we construct a concrete dam in a river, it disrupts what we might call 'natural information content' in the channel. In fact, if you were to go to this dam (Figure 2) while it was running and grasp the handrail really tight, your hand would shake because that dam is vibrating at about 20-40 Hz, with complicated overtones. Probably the dominant frequency is in or near the infrasound range.

So inadvertently we are already guiding fish with sound not only because we probably disrupt the natural acoustic background with dams but because the dams themselves are acoustic generators, i.e., they vibrate when water flows through them. We probably are guiding (or misguiding) fish with sound at most dams; we just don't realize it. Obviously we also create all kinds of very intense hydraulic nets that are much different than what the fish might be presented with in its natural environment. We also put relatively small (less than channel width) structures in a fish's way, such as drum screens and inclined screens, and a variety of hydraulic structures, such as intakes or bridges, in a stream channel. As a reminder, what we've heard from our speakers here is that when you place structures in a high-energy flow field, that structure is almost certainly going to vibrate – in fact, you can't make it not vibrate. That structure will generate an acoustical signature and will produce a fine-scale hydrodynamic field, and both the acoustic and hydrodynamic disturbances in the water are well within the sensory capabilities of fish.

I think these issues of how fish respond to underwater sound and fine-scale and coarse-scale hydrodynamic patterns extend much further than just fish guidance and fish protection, because we're really asking how a fish responds to its environment. A couple of other issues are also related to the fish sensory systems. We are altering the underwater acoustic and hydrodynamic environment with habitat restoration, water resources development, fish guidance and fish protection activities, and impact analyses where we change the environment as viewed from the fish's perspective. What we as professionals normally do when we carry out these activities is to use engineering approximation methods which totally ignore the sensory capabilities of fish. So we present to the fish what we think it likes without having made the effort to determine from the fish's perspective whether this is something it would like or not.

I've been trying to understand this area of acoustics and hydrodynamics for some time, although I admit that I am not nearly as sophisticated in acoustics as some of the earlier speakers. What I have gathered from reading and discussions is probably best summed up by A. D. Hawkins (1993): "*Close lo the sound source, if 's not easy to draw a distinction between sound and bulk movements of the medium itself.*" So my short answer is, basically, that fish hear hydrodynamics. If 1 generate any kind of high-energy disturbance in water, I'm going to generate both a hydrodynamic field and an acoustic field. The two are related. In fact, it may be extremely difficult to separate those two fields. So I think a good simplification for someone like me who is not an acoustician is that fish hear hydrodynamics.

Now I would like to integrate what some of the other speakers have said. I would like to look at some signals that occur in the environment that a fish might acquire, signals that would provide information to the fish about where it is or where it's going, or the scales of its environment, and so on. This is not to argue that fish really detect these things, but rather to say that information is out there, and until we better understand and confirm the acoustic data acquisition/processing capability of fish through laboratory and controlled experiments, it might be a good, conservative idea for us to consider that fish may really respond to natural and man-made acoustic and hydrodynamic disturbances in the water.

Figure 3 depicts what I often refer to as my chaotic model of the natural stream environment. Most hydraulic engineers would break-up this system, i.e., discretize it into a series of cells of more or less uniform scales. But when you simplify, you throw away information. If you were to really track what happens to this water as it interacts with the shape that it's in, you would see all kinds of complex hydrodynamic features, some of which the earlier speakers have alluded to. In fact, you can expand this general idea even more, because in this case (Figure 4) the shape stands still and the fluid moves in the high-energy setting, or you can have the medium stand still and the shape move through it (Figure 4) as in this case where a fish is propelling itself through the water. Either way, the disturbance is generating acoustic and hydraulic information that the fish's sensory system is beautifully attuned to collect.

When there is a disturbance in water, whatever the cause, the acoustic and hydrodynamic patterns that propagate are going to be related to the scale, energy level, duration, shape, and magnitude of the disturbance – all the pieces of information about the disturbance that may interest a fish. This information is packaged in both the acoustics and fine- and coarse-scale hydrodynamics. Ii you survey the literature about fish hearing with an emphasis on identifying behaviors that would require information about the fish's environ-ment, you will find many reasons why a fish would be interested in acoustics from a biological perspective and also from a physical-structure perspective:

(1) The aquatic environment is rich in acoustic information. Any disturbance in the fluid medium generates signals related to scale, energy level, duration, shape, and magnitude of disburbance.

(2) Fish are able to transduce this information.

(3) Fish respond to this information for

- obtaining prey
- avoiding predators
- communicating
- distant "touching"
- locating sources
- navigating
- mate location/courting
- schooling

I had an opportunity to read a book by Robert Urich (1986) called *Ambient Noise in the Ocean* in which he was bemoaning the fact that the researchers looking for submarines are constantly assailed by all the complexities of the acoustic background. The characteristics of the acoustic background are related to water depth (when depth is <0.25 wavelength, that frequency is eliminated), temperature structure, surface wave action, waves breaking on the shoreline, ocean currents, hydraulics, shipping activity, and other attributes of the immediate hydraulic environment. Perhaps from a fish's view, Urich's perspective is backwards. For a fish, noise is that pure tone that's being sent out in efforts to search for the submarine. However, the acoustic background is not noise-it's information about the environment, ii we knew how to extract it.

I'd like to look at some relatively small-scale signals that occur in a flume setting. What I want to show next (Figure 5; van Dyke 1982) is approximated by this visualization of a flow field, i.e., that in this setting the flow is moving from left to right. This small structure in the flow field causes the flow to separate from the bottom. And you would ordinarily think that flow feature wouldn't extend very far downstream from the disturbance, although in reality – measured as velocity pattern – it extends quite far. Run #1 is maybe 1 times the height of that feature; Run #7 is 40 times the height of that feature, and you can see that it travels downstream a distance near 40 times the height of that feature (Figure 6; Nelson et al. 1995). So if a fish has a sensory system, like a lateral-line system composed of linear arrays of fine-scale pressure sensors, flow features like these on the bottom (Figure 5) will function as road signs providing the fish with information about the physical structure of its surroundings.

We have developed a sensor system we call MSFS (aka "MISS FISH") that we can use to emulate the sensory capabilities of a fish. Like a living fish, this probe has series of very small sensing elements (piezoelectric film) that are arrayed more or less like a lateral-line system. We can achieve a small peek into the fish's world by acquiring fine-scale pressure data in time and space and evaluating the pressure patterns right and left and from front to back on the sensor system. We can employ signal-processing methods to extract information by analyzing the single sensors in the time and frequency domain and integrating across sensors by evaluating time of arrival of the signals to identify phase shifts across different sensors.

Ordinarily, if we visually describe the flow pattern in this flume (Figure 7), we are unable to discern information about flow fields without special flow visualization methods. However, flow fields in flumes can exhibit surprisingly complicated behaviors. On this slide (Figure 8) we have a representation of the sensor system; that's the right flume wall and that's the left flume wall. Note that the sensor system is located closer to one wall of the flume than the other. On this plot, the x-axis represents different channels: The y-axis is time and the x-axis is amplitude. In this visualization, you can actually see the turbulence rolling off the flume wall as water flows through the flume by the peaks in signal amplitude for those sensors closest to the flume wall. I've observed fish in flumes many times, and I've always been amazed at how talented they are at finding and utilizing the slightest hydrodynamic anomalies in the flume. I have seen fish seek refuge behind wields connecting the plates comprising the flume bottom or behind the smallest structural members that support screens or other structures that are being evaluated. I think this and the previous figure give you an idea of what signals that fish could be responding to in these environments. Note also that these are extremely obvious signals, once you know where and how to look for them, certainly very obvious to a fish.

I have also looked at relationships between substrate size and pressure signals generated by water flow moving over these substrates. We observe much the same pattern as that observed for pressure signals generated by the flume wall (Figure 9) . That is, flow moving over sub-strate that varies in both sorting and size and the percent of imbcddedness will also generate small-scale differences in pressure patterns related to the changes in substrate. Unfortunately, I couldn't find the figure that presents the pressure fields associated with different substrates. However, it was very obvious that the frequency domain over a relatively small substrate like pea gravel was much different than the frequency pattern associated with flow moving over gravel of maybe 1 inch diameter. That's germane to a fish, or almost any aquatic organism, because that boundary-layer effect is important to explain many behavioral responses of aquatic organisms in streams.

Now I will present an observation we made in a sink about how a fish may be able to determine its lateral position that is perhaps more elegant and less obvious than pressure signals propagating from substrates or flume walls. For this example, we put a pressure sensor in a sink and generated a reciprocating wave in the sink by moving our hand back and forth in the water. We were able to determine the approximate location of the sensor in the sink by the pattern of timing in the returns of the wave pressure peaks. If the sensor is in the middle of the sink (from left to right), the return waves require the same time to rebound from the sink wall and return to the sensor. However, if you were closer to one side, you would see two quick waves and a long wave. In a natural channel, relatively small disturbances by wind or surging flow may also generate a lateral (perpendicular to the long axis of the channel) wave (similar to seiching in a lake). I should point out that the signals were quite obvious, and there was no uncertainty when our probe was in the middle of the sink and when it wasn't. It may be that something as simple as wind-driven seiching in a channel provides information to a fish about its lateral position in the channel. Of course this is a speculation.

In the example I just completed, we speculated on how a fish could acquire information as to its lateral position in the channel. Now I'll present some musings of how a fish could determine its depth from the background acoustics. I pulled this information (Figure 10) from the literature (Urich 1986). This is a frequency spectrum during periods of relative calm, and this line is the frequency spectrum during a wind gust. Wind gusts are responsible for a very definite increase in frequencies from -50 Hz to -100 Hz. The significance of this relationship requires that we revisit the relationship between water depth and the sound frequencies that propagate as a function of depth (water depth must be greater than four times the wavelength or that frequency will not propagate). If the fish's challenge is to locate the deepest part of the channel, this relationship suggests that the fish should search for the lowest frequencies because the deepest part of the channel would be where the lowest frequencies occur in the acoustic background.

Recently we made measurements in a river with a hydrophone. Admittedly, these are preliminary data collected about 5 years ago when we were still learning how to collect this type of information. We are really proud of this research stick – we didn't even order it out of a catalog (Figure 11). It suspends a hydrophone in the water. In this study, we were attempting to determine if different hydraulic features have different acoustic signatures. Thus, if a fish were able to acquire this information, then it would perhaps be able to navigate through a complicated hydraulic regime. We think that our premise is true, that different hydraulic features do indeed have different acoustic (or pressure) signatures. This slide depicts a stream channel (Figure 12) just downstream of a hydraulic jump, and what's interesting here is that most of the energy is in the lower frequencies; in fact, this vertical reference line is at 33 Hz.

Up to this point, we have been discussing how physical features in the aquatic environment that are significant to a fish may be associated with specific acoustic or pressure signatures. Now I would like to demonstrate that there are also similar signatures associated with aquatic organisms that are generated as they move through the fluid medium. This is a picture of MSFS (Figure 13). This particular model has four sensors on each side along this line that emulate the trunk lateral line and four pairs of sensors that emulate the supra-orbital and submaxillary parts of the lateral line. We forced a fish to swim by the probe to determine if we could measure and describe the acoustic/hydrodynamic pressures associated with a swimming fish. We think this is the signal associated with a swimming fish (Figure 14). We repeated the experiment with a goldfish and, in this case, performed some complicated signal processing to identify the signature of the swimming fish shown on this slide (Figure 15). The ‘punch line’ here is that the dominant frequencies associated with the swimming fish were in the infrasound range.

I want to emphasize that there is a tremendous amount of information available to a fish in the environment in the infrasound range. And I think there’s much more going on than just predator avoidance as many believe. I can’t believe that fish aren’t utilizing the full range of information in the acoustic and hydraulic fields associated with underwater disturbances (although there are probably subtleties in processing by the fish to acquire this information that we don’t fully appreciate).

Now I’d like us to think about hydraulic structures. This is a wedge-wire bar screen located at a dam on the east coast (Figure 16). When water passes through this structure at 5-6 fps, there’s absolutely no doubt that it will vibrate. I know of one case where an effort was made to measure the sounds associated with an operating dam in the context of fish guidance, and that was by Jim Anderson on the Columbia River (Anderson et al. 1989). Given the known sensitivity of salmon to infrasound (<20 Hz), I find it hard to believe that these sound fields generated by vibrating structures would not have an impact on fish behavior. In fact, it’s well known that various intakes at a single power plant will have different entrainment characteristics. It might be reasonable to blame this variation in entrainment characteristics on the acoustics and fine-scale hydrodynamics associated with water flow through the structure. I don’t think that we appreciate how the acoustical and fine-scale hydrodynamic patterns can be influenced by the presence of hydraulic structures placed in the flow. Complicated hydraulic structures like screens of various designs, perhaps reinforced with various combinations of bars or reinforcing structures on the back, will have a large effect on both the acoustics and fine-scale hydrodynamics at the screen surface (Figure 17). It ‘s something that we have never really looked at for screen design, and it almost begs for some attention.

I’ll try to wrap all this up for you and generate a framework that we could use to integrate fish behavior, sensory biology, and hydraulic design. I think everyone in this room has the objective of designing fish-friendly structures. We want to design structures that communicate to the fish where they need to be and at what depth. If we are able to construct effective guidance systems, the chances of fish bypassing the dam are much greater. However, we’ve never had a suite of guiding concepts that would allow us to achieve this goal; our activities have all been rather hit or miss. Sometimes we’ve been very lucky,as with blueback herring, and sometimes we’re not very lucky at all, which seems to be most of the time. So I propose that we expand these concepts. We need to work our way all the way back to natural stimuli that fish acquire and process to assist the decisions that they must make to survive in the aquatic environment. I’ve tried to do that during my presentation, to give you a flavor of the kinds of acoustic and hydrodynamic signals that convey important information about the aquatic environment. We need to understand natural stimuli in the context of the fish sensory system and also how fish process that information (Figure 18). This understanding can help us discern whether our signals are louder, more intense, or in the same range as natural stimuli. We can determine how our flow field compares to a real flow field. Then we can invoke these concepts and actually manipulate the aquatic environment near dams to build better bypass and guidance systems.

There are, of course, two different ways of affecting the behavior of fish at intakes. One is the use of brute force, the sledge-hammer approach: We can place guidance systems in environments at such high velocities that the ability of the fish to make decisions about its position in the system is minimized; in essence, we modify only the hydraulic environment. The second approach is more elegant: Because fish probably use only a part of all of the information available to them, it may be quite reasonable that we project only that part of the information that they're using to "forge" a flow feature. That is, we provide them only with the signal of that feature and nothing else.

When I first started all of this work, I had a very simplistic view of hydrodynamics and fish hearing and behavior. Now I see the world from the standpoint of this billfish or this little prey fish that he's about to swallow (Figure 19). When that fish gives a powerful push with that tail, it generates a really interesting hydrodynamic field, and undoubtedly an acoustic field. And as that fish rushes, it's generating tremendous amounts of information, just as a little fish does moving through the fluid medium. So there are tremendous amounts of information in water available to a fish. When we build structures, when we modify the aquatic environment, we inadvertently affect that environment and the fish because we don't appreciate the natural environment the fish is in and its rich content of stimuli.

Figure 1

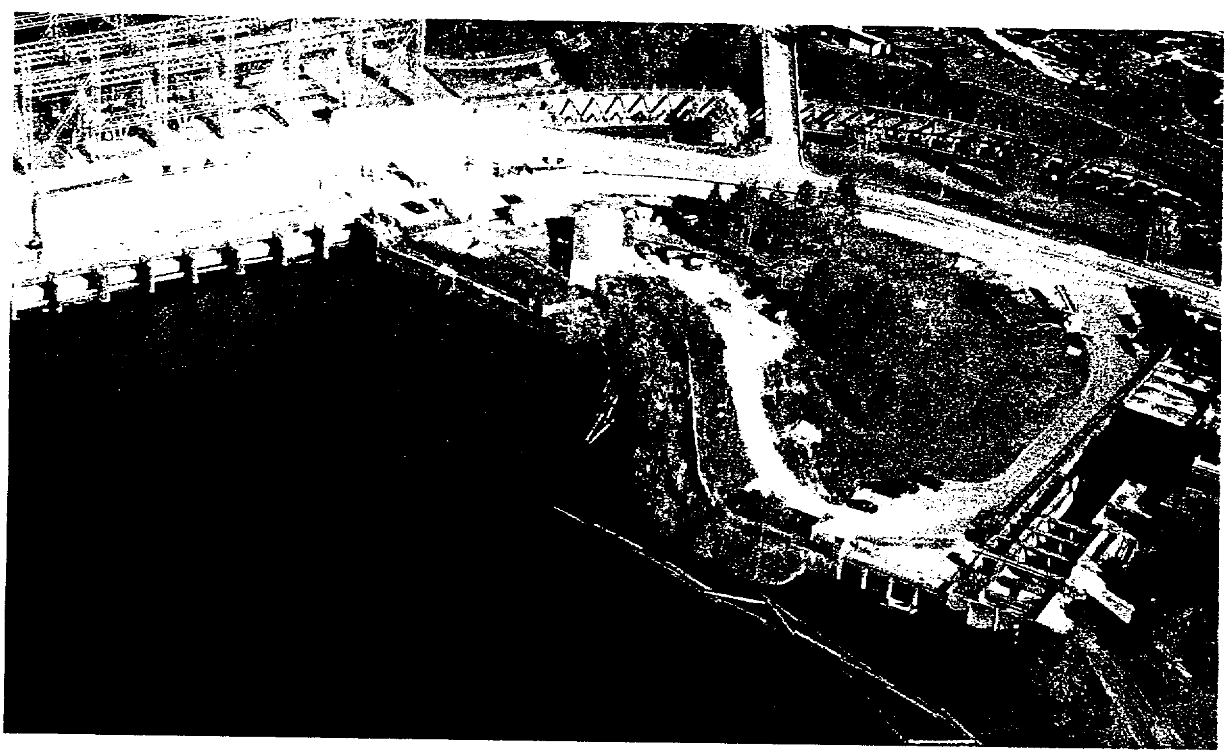


Figure 2

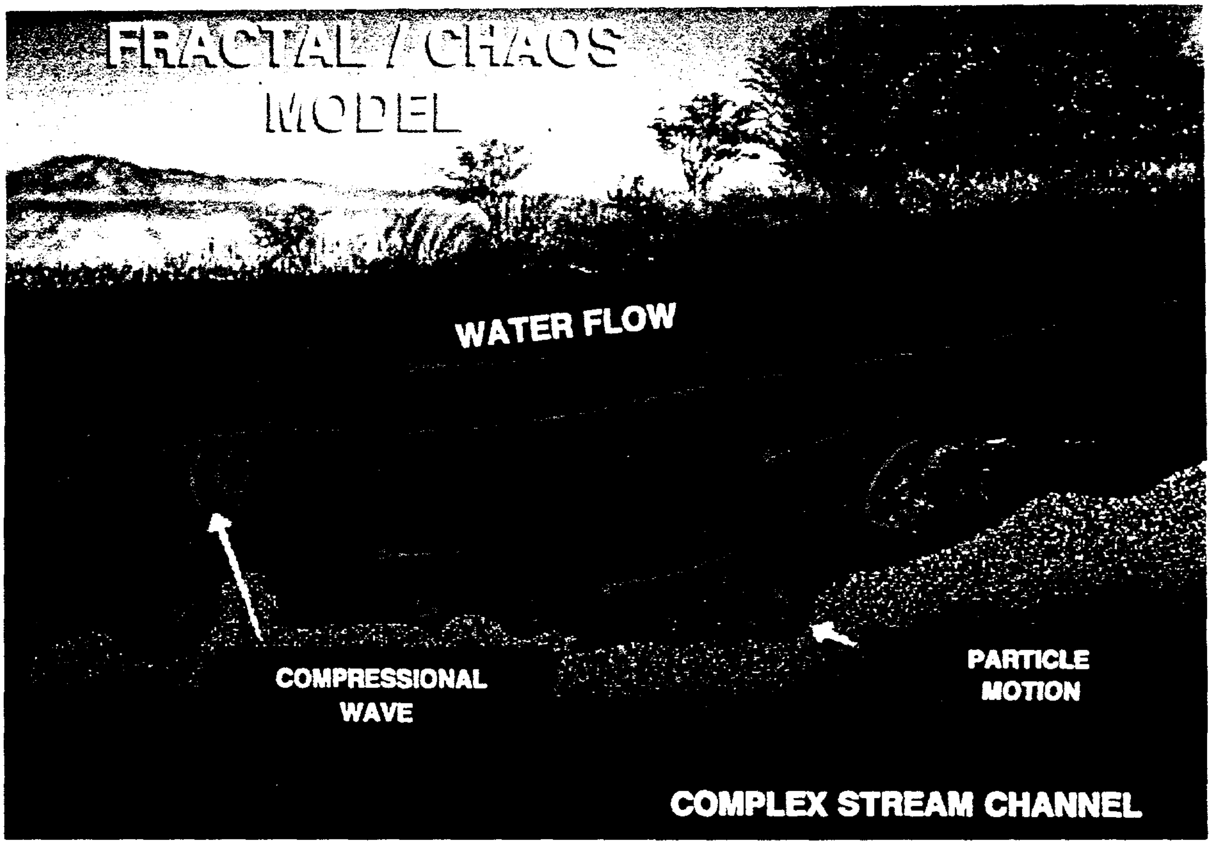


Figure 3

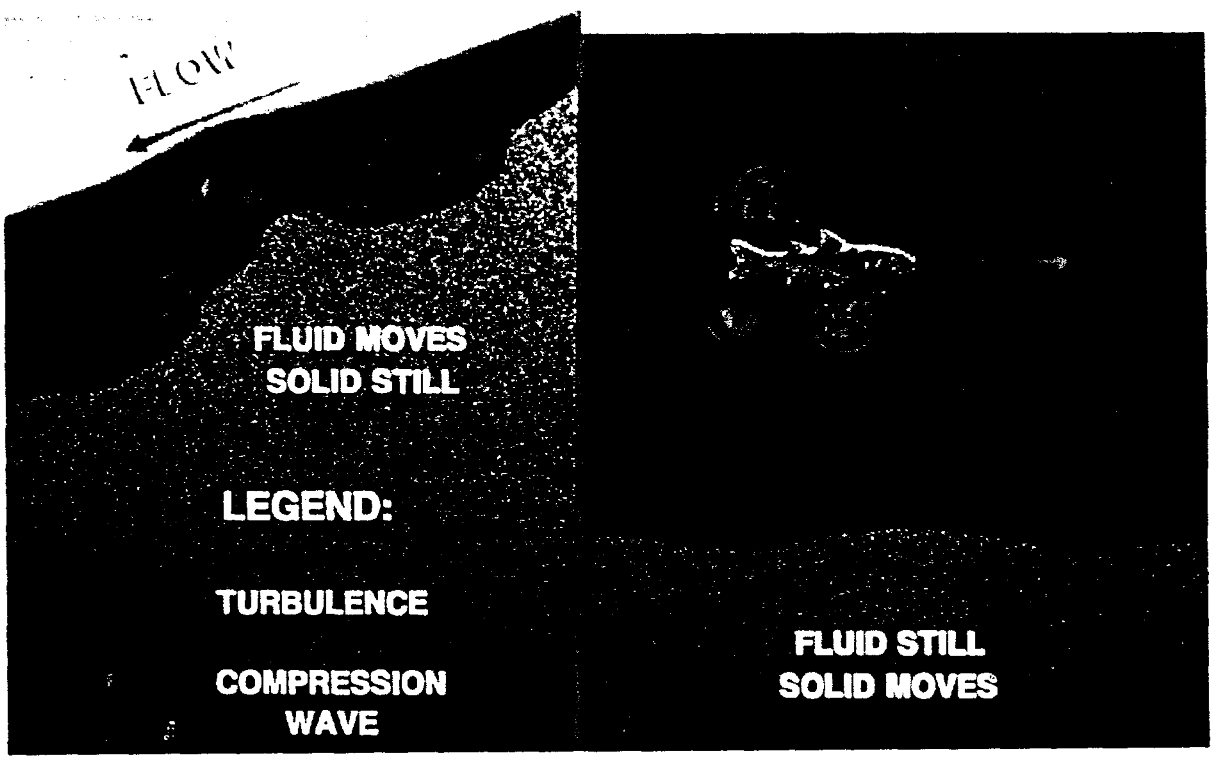


Figure 4

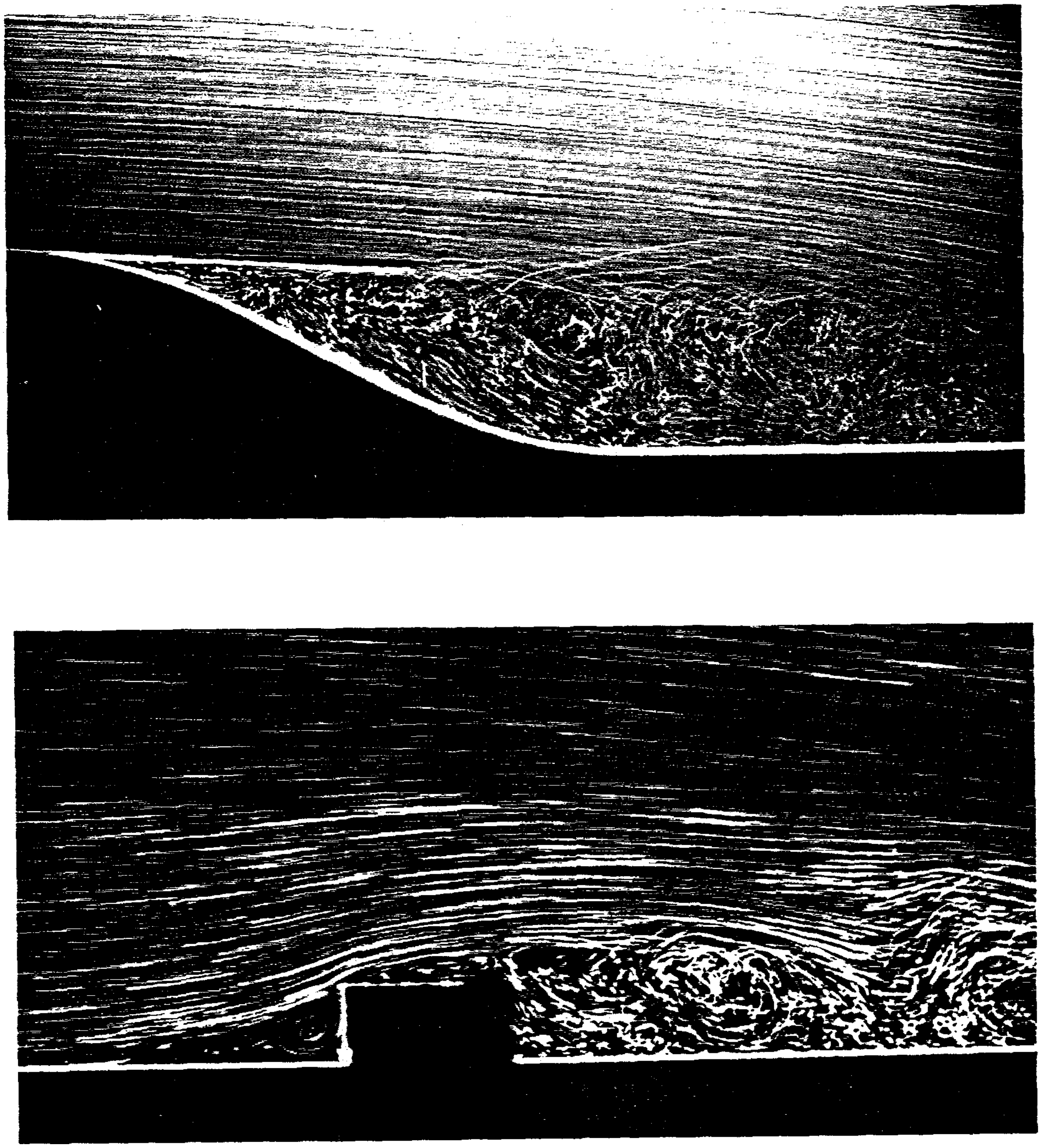
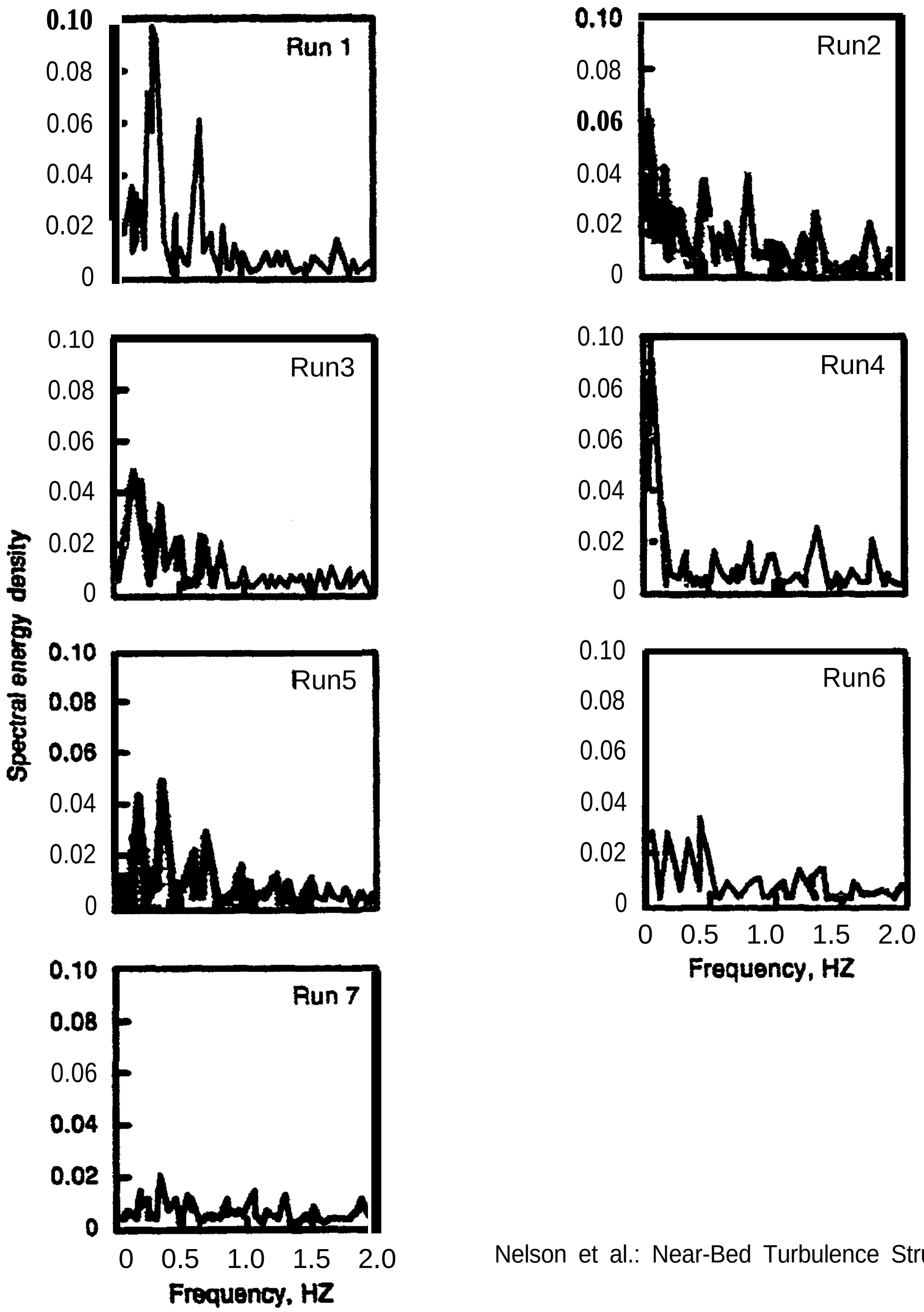


Figure 5

Spectral energy densities of the turbulent fluctuations in the streamwise velocities



Nelson et al.: Near-Bed Turbulence Structure

Figure 6

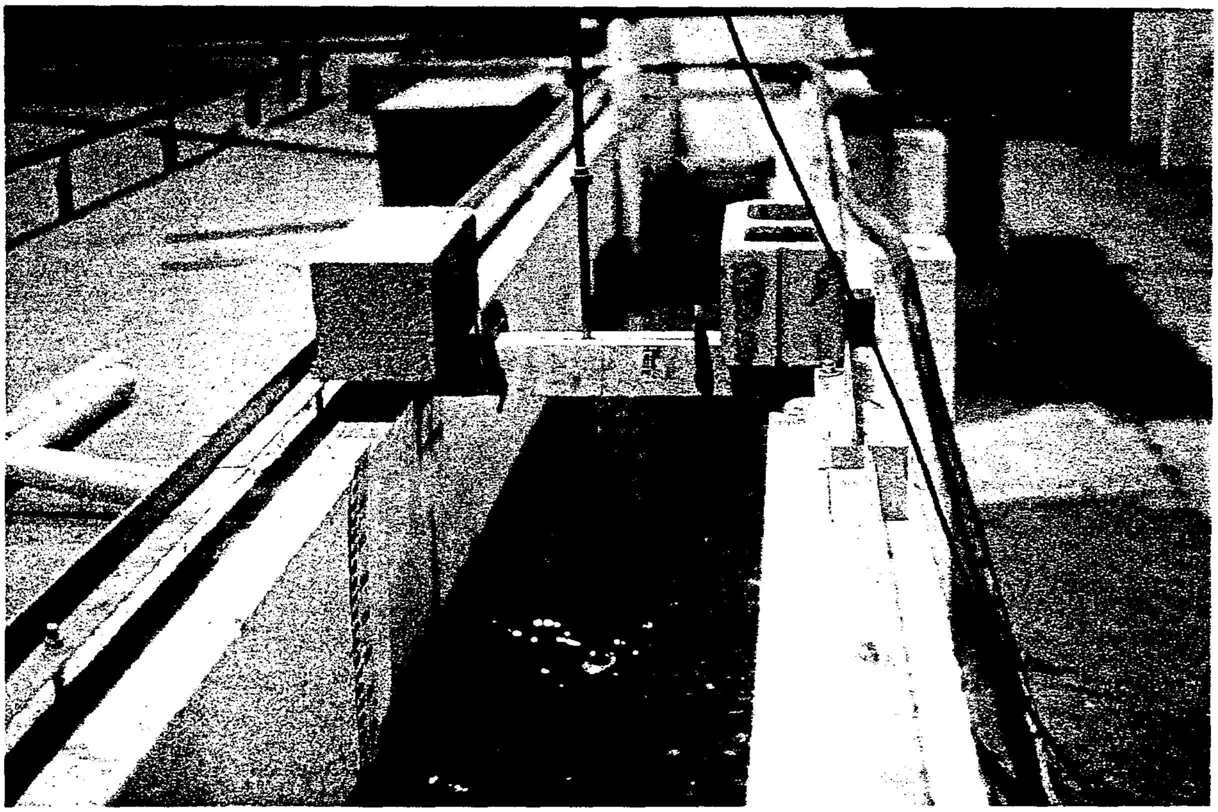


Figure 7

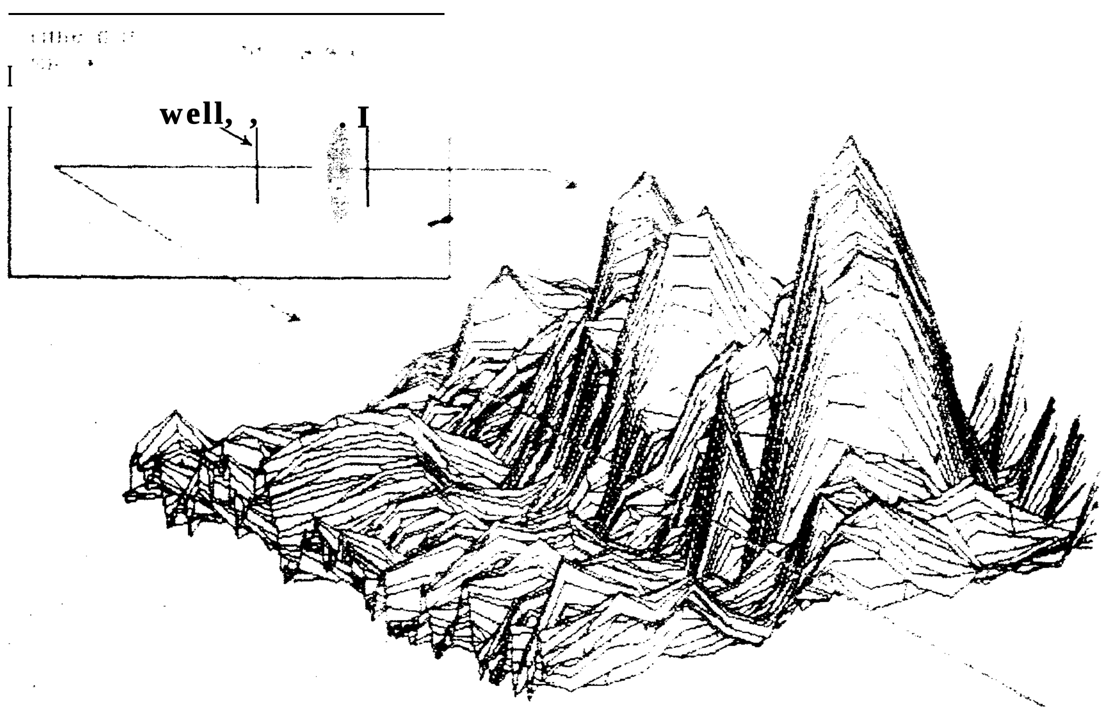


Figure 8

Figure 9

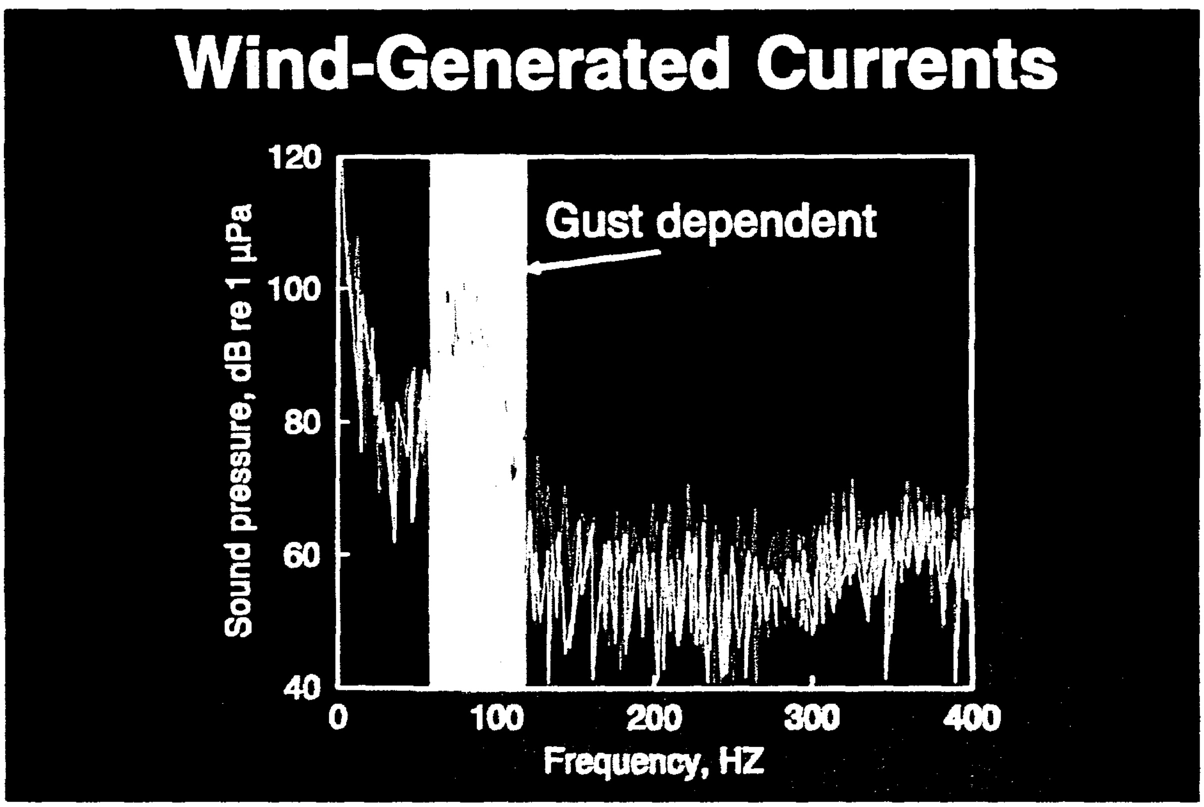


Figure 10

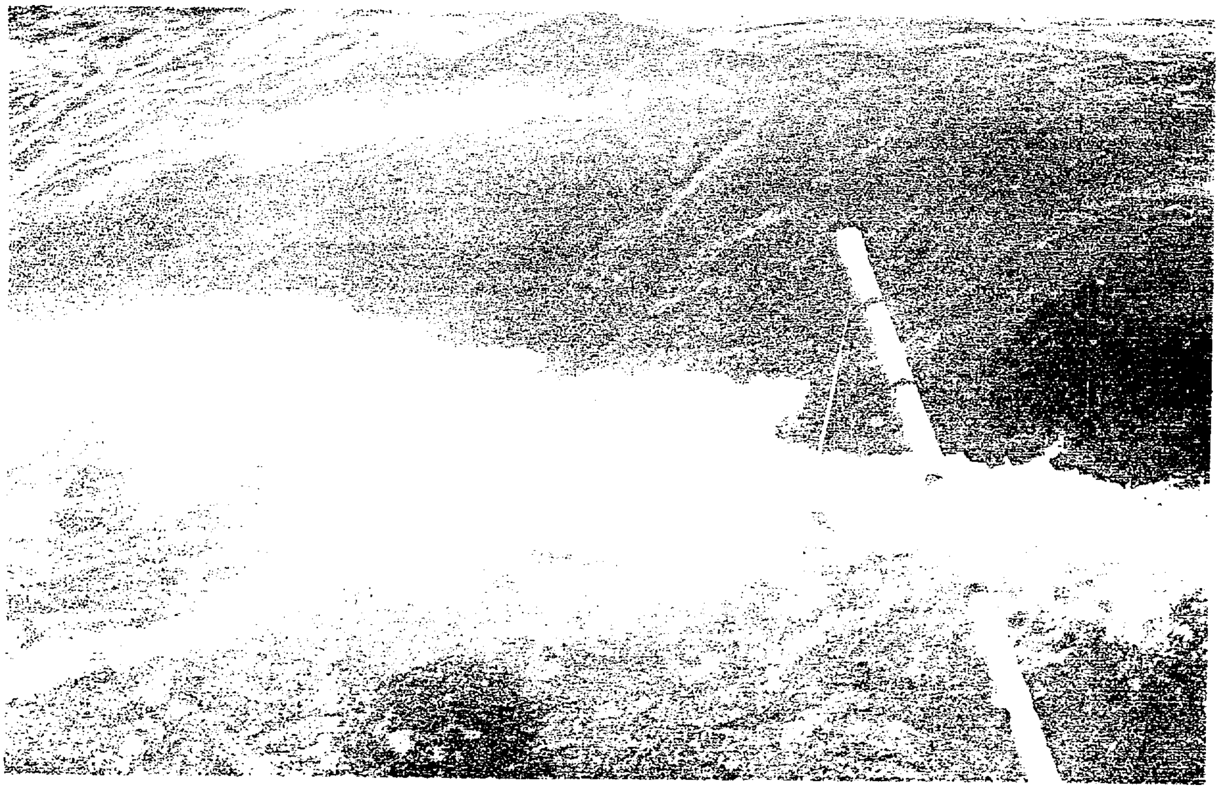


Figure 11

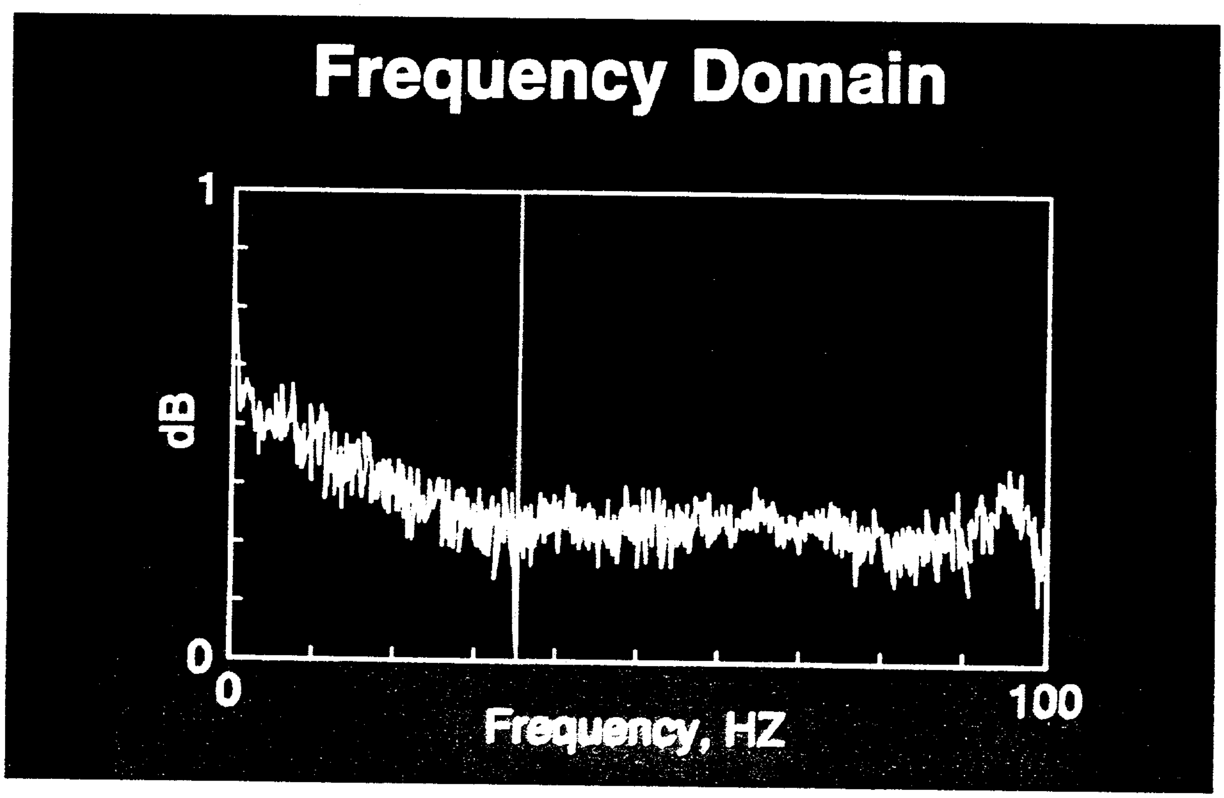


Figure 12

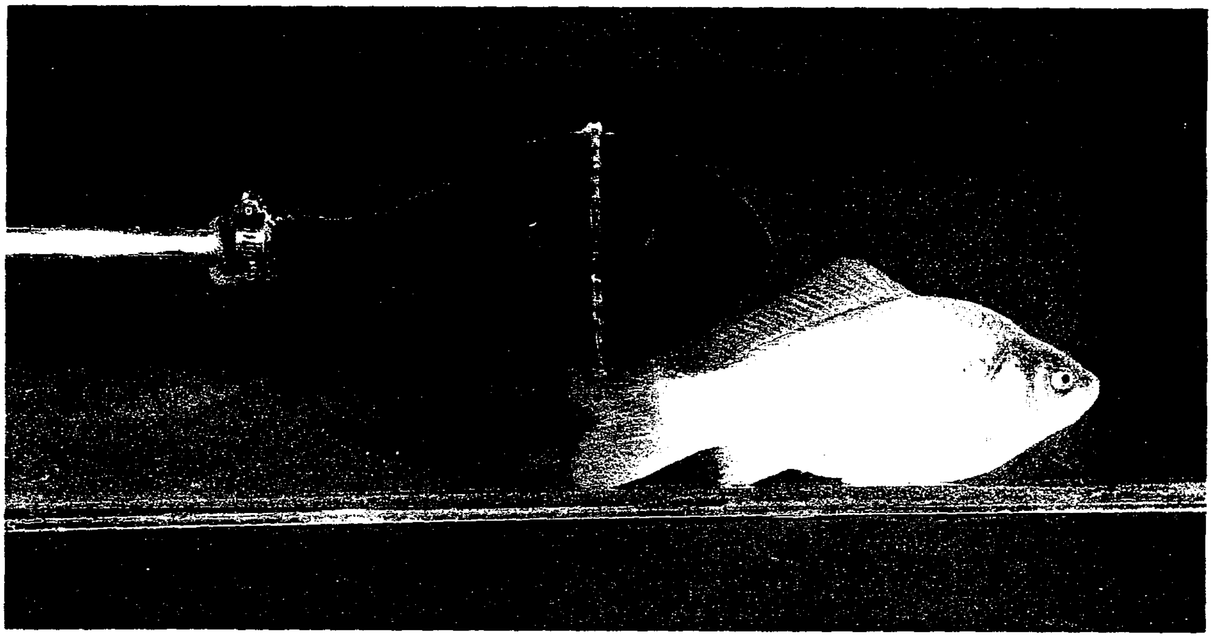


Figure 13

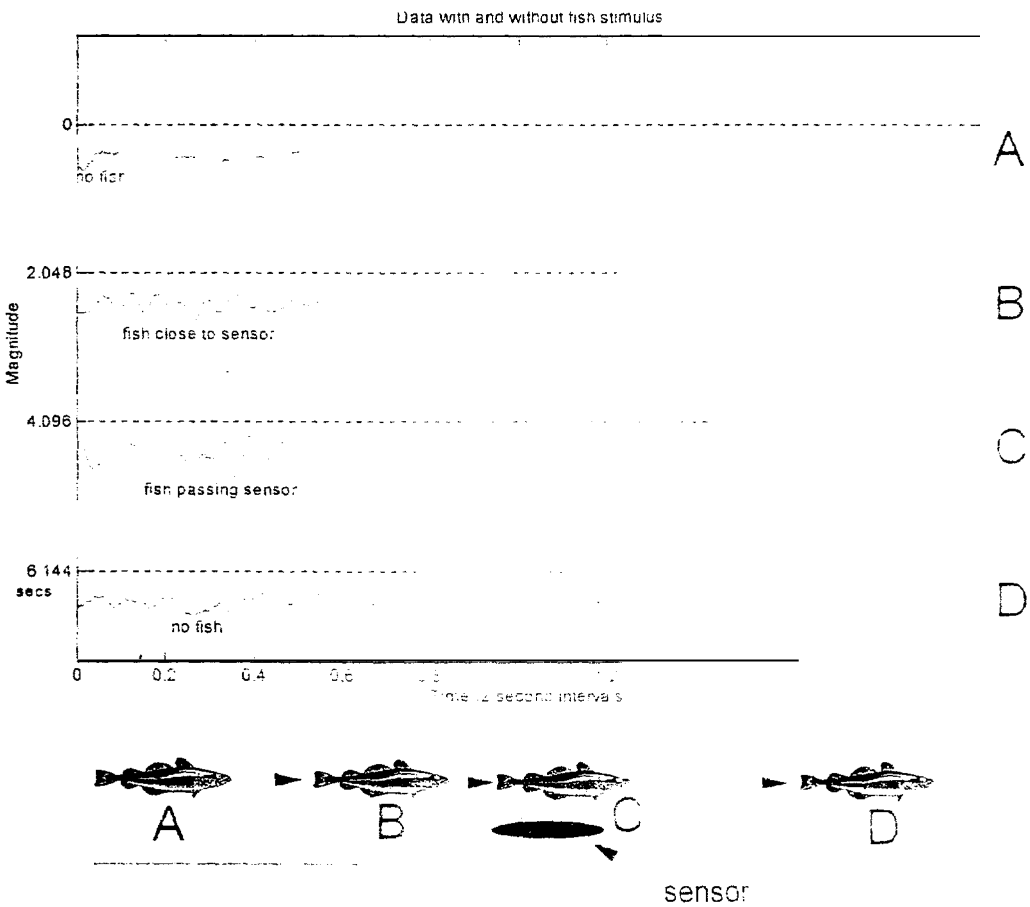


Figure 14

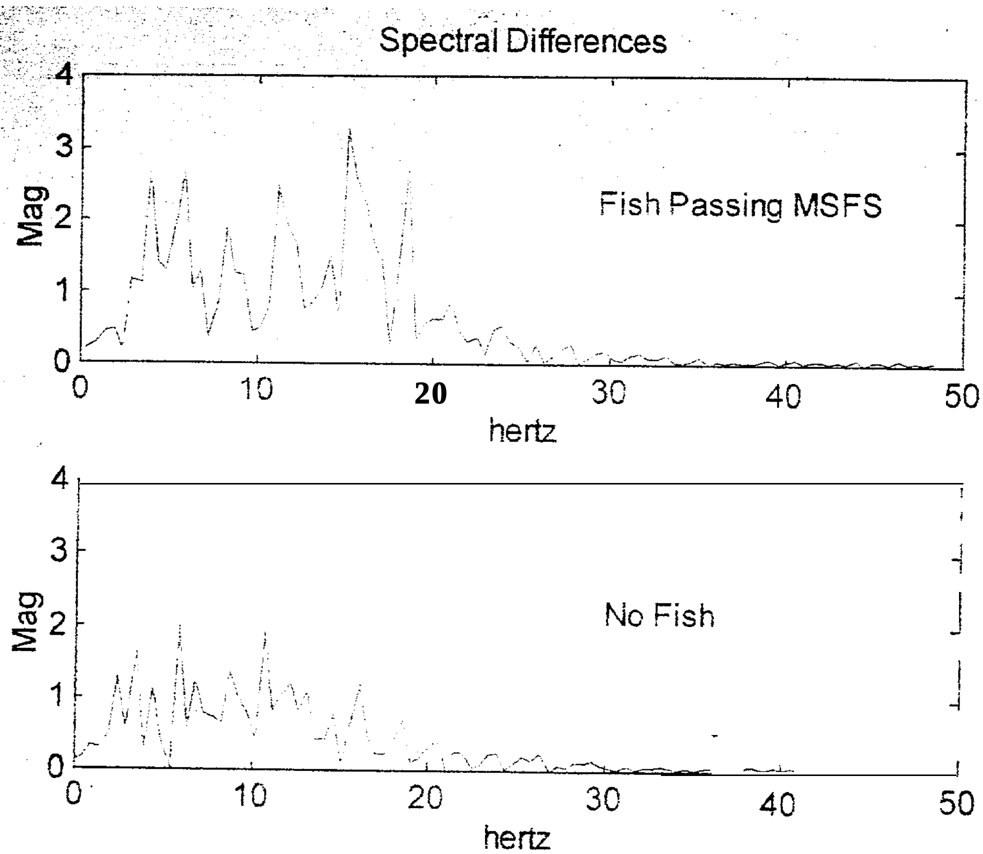


Figure 15

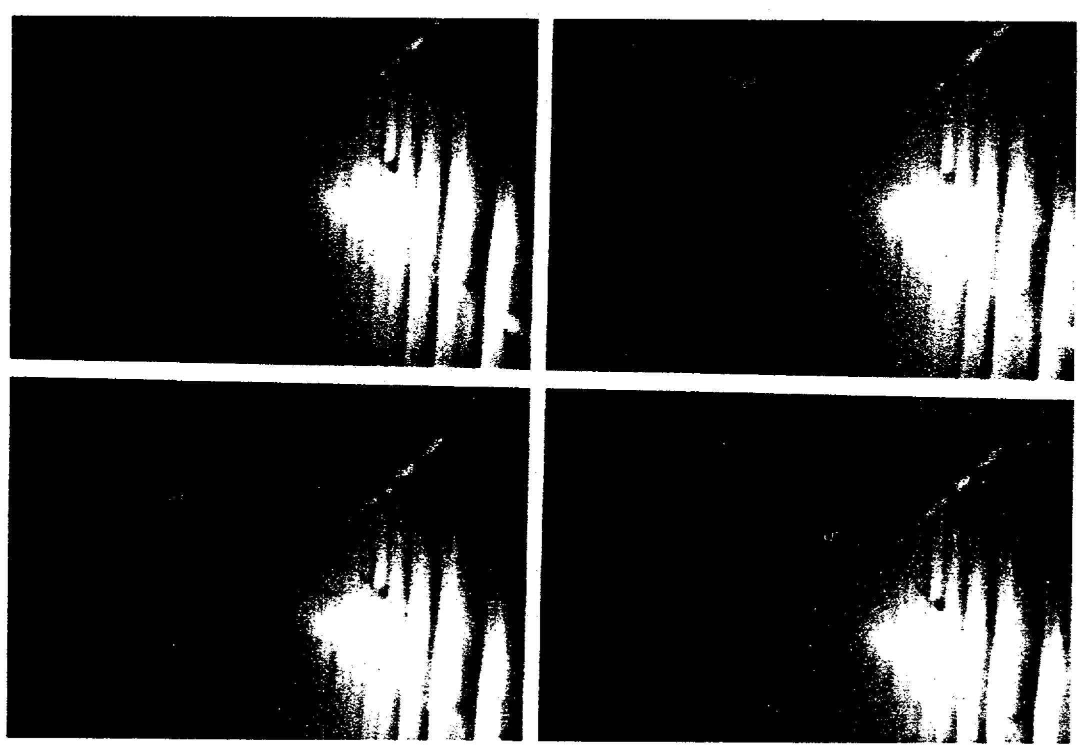


Figure 16

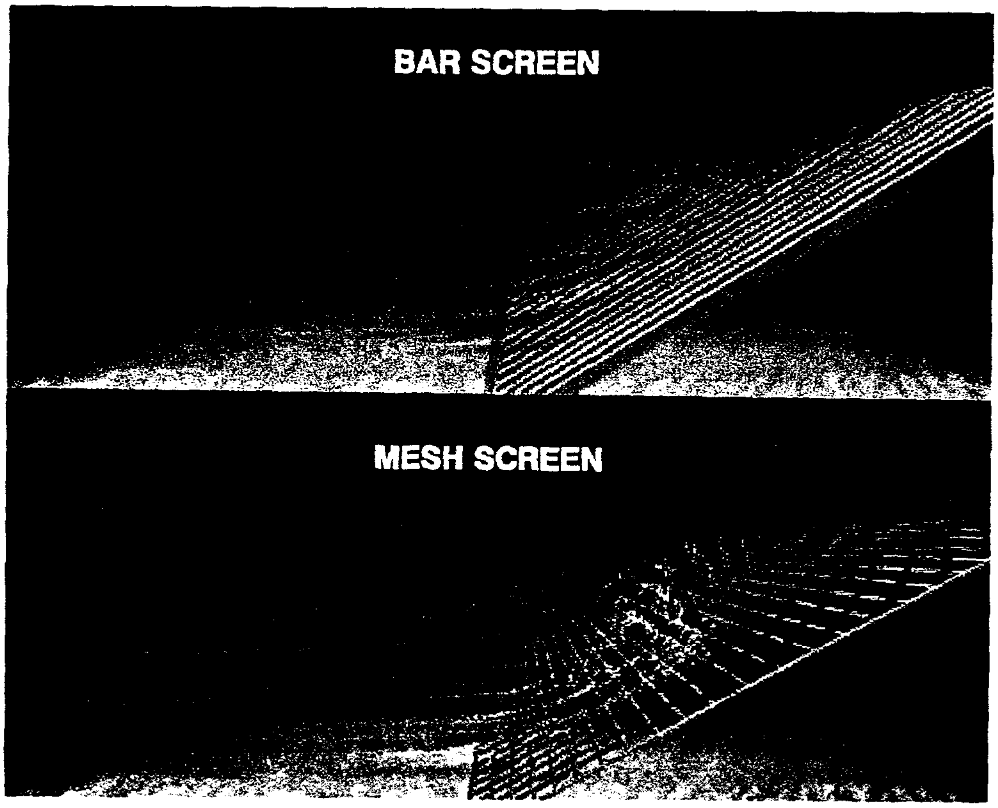


Figure 17

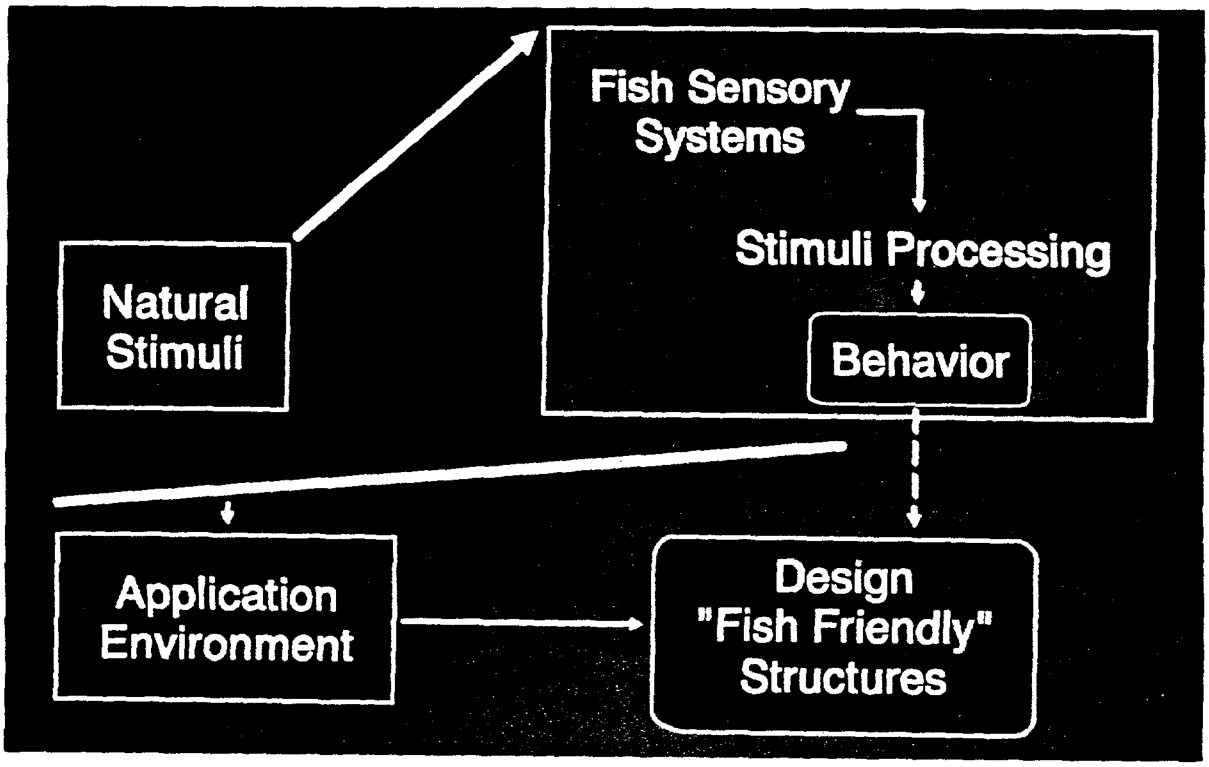


Figure 18

Figure 19

Ultrasound Deterrence: Alewife at a Nuclear Generating Station in New York

Dr. Dennis Dunning
New York Power Authority

This morning we heard from speakers who talked about the response of fish to sounds, and they focused on technical details. John Nestler changed gears and talked more philosophically about how natural sounds are relevant to fish. In this session, we will address the issue of whether any of these acoustic devices actually work. Which gives me a nice lead-in to a conclusion that appeared in the Office of Technology Assessment report: "Results of acoustic studies are quite variable, range from totally unsuccessful in controlling behavior to demonstrating potential usefulness for a few species." An important question is, how come? Based on the section on downstream migration, there are significant deficiencies in study and analytical designs in a lot of what's been done with sound to date.

What I'd like you to focus on during this next session is what kinds of information are being used, and is it rigorous. My presentation will deal with a sequence of studies that we used to take an unproven behavioral technology, apply it to a power plant, and demonstrate its success as a fish-protection measure. The facility is the James A. FitzPatrick Nuclear Power Plant. The practical issue is the federal Clean Water Act, Section 316 B, which requires that the design, construction, and capacity of the intake of this facility and all other point-source discharges reflect the best technology available for minimizing adverse environmental impact. Ignoring for the moment the absence of a universally accepted definition of 'adverse environmental impact', and the absence of agreement on what is 'best available technology', what we were trying to do with the resource agency in New York State was find a better way to save fish than conventional screens.

We had a problem with a species of fish called the alewife. At the Fitzpatrick plant, 80% of total annual impingement was comprised of alewives, 90% of that in the spring was alewives. The actual number that died ranges from -66,000 to 523,000. Intake flows are on the order of 2.3 X 10^6 m^3/day, i.e -330,000 gallons/min. Alewives are important because back in the 1970s, New York State undertook a very aggressive stocking plan for salmonids. The salmonid fisheries are primarily dependent upon alewives, and the program was so aggressive that by 1991 predator demand in Lake Ontario, on which the Fitzpatrick plant is located, was equal to the total annual production of pelagic species. A growing fear was that a cold winter could cause a mass mortality of alewives, that in turn could lead to a crash in the alewife population. Our objective was to find a way to reduce alewife mortalitv.

Interestingly, alewives were not always considered an important forage species. Before the introduction of salmonids, it was not an uncommon site on the Great Lakes to see mass die-offs of alewives in the spring, creating a nuisance and a health hazard along beach fronts and in harbors. But somebody managed to turn garbage into gold.

Our work was based on John Nestler's observation that high-frequency sound caused an avoidance response in blueback herring. We constructed a cage and put two videocameras on it to observe the behavior of alewives undisturbed by high-frequency sound. Then we took a high-frequency transducer, placed it 10 m away from the cage, and turned on the sound to see what kind of response occurred. We varied the sound from 110 to 150 kHz, and we varied the sound-pressure level until we were reasonably certain we knew which frequencies and sound-pressure levels would work most effectively. The response was rather dramatic. Turn the sound on, and the fish go from one end of the cage to the other. Undisturbed, they just circle the cage.

Next, we blocked off half of the cage with a sound-insulating material and left the other half exposed. We let fish swim around the cagethat we divided into four quadrants. As fish swam around the cage, we recorded their movements into and out of a quadrant as a count. Without high-frequency sound, there were equal counts among quadrants. When we turned on the sound, the fish never entered the two quadrants that were ensonified. This was for a period up to 150 min. The only problem is that this was all done during the day. When we observed the fish at night, their behavior changed; they weren't as tightly schooled, they didn't move as much, they didn't respond as strongly.

Having established that alewives can respond strongly to high-frequency sound, we decided it was time to take this concept into the field. Our testing in the quarry was done during the winter of 1989. ESEERCO, who provided most of the funding for the remainder of our work, made a unique commitment allowing us to do reconnaissance work in the spring of 1990 to determine the spatial and temporal distribution of fish, background noise, and if undesirable reflections were present. In the winter of 1990, we designed a system.

At the Fitzpatrick plant, the intake isabout a half-mile offshore. About 200 ft further offshore is a large discharge diffuser. The water coming out of this structure is -17°C higher than ambient. It creates turbulence that is visible at the surface when the reactor is at full power. One of the things I told you is that we didn't get a good response from the alewives at night in quarry tests. During reconnaissance, we found that the large numbers of alewives were near the intake at night. This condition should have provided the most severe test of the system.

The Fitzpatrick intake has four bays. There are trash racks in front of each of the bays, and it was on these trash racks that we placed the transducers. We placed 16 narrow-beam transducers and 4 wide-beam transducers across the face of the intake, and we placed one transducer -31 m from the face of the intake, facing the intake, to measure the density of fish (numbers / 100 m^3) so we could get an independent check on impingement. We selected the Fitzpatrick plant partly because there is another facility about a mile to the west, also with an offshore intake, that served as a control. The flow of fish and the general water flow of Lake Ontario near Nine Mile Point is west to east. By the time the fish reached the JAF intake, they would have gone past our control site before being exposed to high-frequency sound.

We used 16 narrow-beam transducers and the four wide-beam transducers to cover the entire front of the intake. The first thing we tried to do with the fish in front of the Fitzpatrick intake was to duplicate the strong response we got with caged fish This (Figure 1) is an echogram. The monitoring transducer is at the top and the face of the intake is at the bottom. The x-axis is time in minutes. The dark areas represent a highdensity of fish. When the transducers were turned on – sound was produced for a half-second every second for about 5 min – the fish disappeared. It took over 10 min after the transducers were turned off before the density of fish returned to the pre-test level. We did this test about 15 times to convince ourselves that it would work, and each time we got very similar results, i.e., we replicated the quarry test results.

Next, we planned to run the system for 30 days. And as luck would have it, after 8 days the reactor shut down, the flow was reduced by a third, and so we had 8 days of full flow at both plants. During the first 8 days of testing, we calculated an 87% reduction in impingement of alewives at the Fitzpatrick intake.

During the same 8 days, the hydroacoustic information indicated that fish density in front of the intake was reduced by 85 %. When Fitzpatrick plant was down, reduction was much lower (29%). If you remember, offshore of the intake there was a large discharge diffuser. We hypothesized that when the plant was running at full power, there was a thermal barrier that prevented fish from approaching the intake from the rear. Unfortunately, we hadn't thought of ensonifying the back side of that intake.

In the spring of 1993, we added five more transducers to the array. These transducers were intended to prevent fish from coming along the top and sides of the intake and slipping into the intake opening. What I didn't mention earlier is that the transducer located 30 m offshore had a blind spot of about 1 m in front of the intake. So anything that came along the sides could have snuck into the intake opening and not be detected. In 1993, instead of turning the system on and off for days at a time, we decided to turn it on for 90 days. Our primary question was whether the system would be more effective with the five new transducers. Because the winter of '92-'93 was extremely cold, we were also looking to see if this affected fish and, thus, the effectiveness of our system.

To analyze the 1993 test, we used a BACIP design, a 'before/after controlled impact pairs' design to test the difference among selected sets of paired impingement samples, It differs from a single two-factor design in that the control- and impact-sites' appearance are for each day. The difference between impingement counts at Fitzpatrick and the control site on the same day is an observation. The "after" samples consisted of paired daily impingement counts when the deterrence system was operating. The "before" samples consisted of daily impingement counts collected during the same period in years when the deterrence system did not operate. The overall reduction in impingement that we calculated for 1993 was 81–84%. Adjusting for the cold winter, the estimate was 87%, the estimated reduction in impingement in 1991.

In summary, we produced a strong directional response under controlled conditions, replicated that response under field conditions with fish unaffected by capture and handling, estimated effectiveness using hydroacoustic and impingement data in 1991, and confirmed the effectiveness in 1993 using impingement data and a different analytical design than that used in 1991. We believe that collectively these studies constitute successful demonstration of a new fish-protection measure. These results led the New York State Department of Environmental Conservation to determine that high-frequency sound for alewives was in fact the 'best available technology' for reducing mortality of alewives at the Fitzpatrick plant.

We believe that these results can be replicated at just about any site if you control for sound reflections, check background noise, and make sure your sound field has no holes in it. We believe that out study meets all the requirements for a technology demonstration, and there is no need to test this at a wide variety of sites to demonstrate that it works. Testing at another site would indicate whether the system has been engineered and deployed properly at that site.

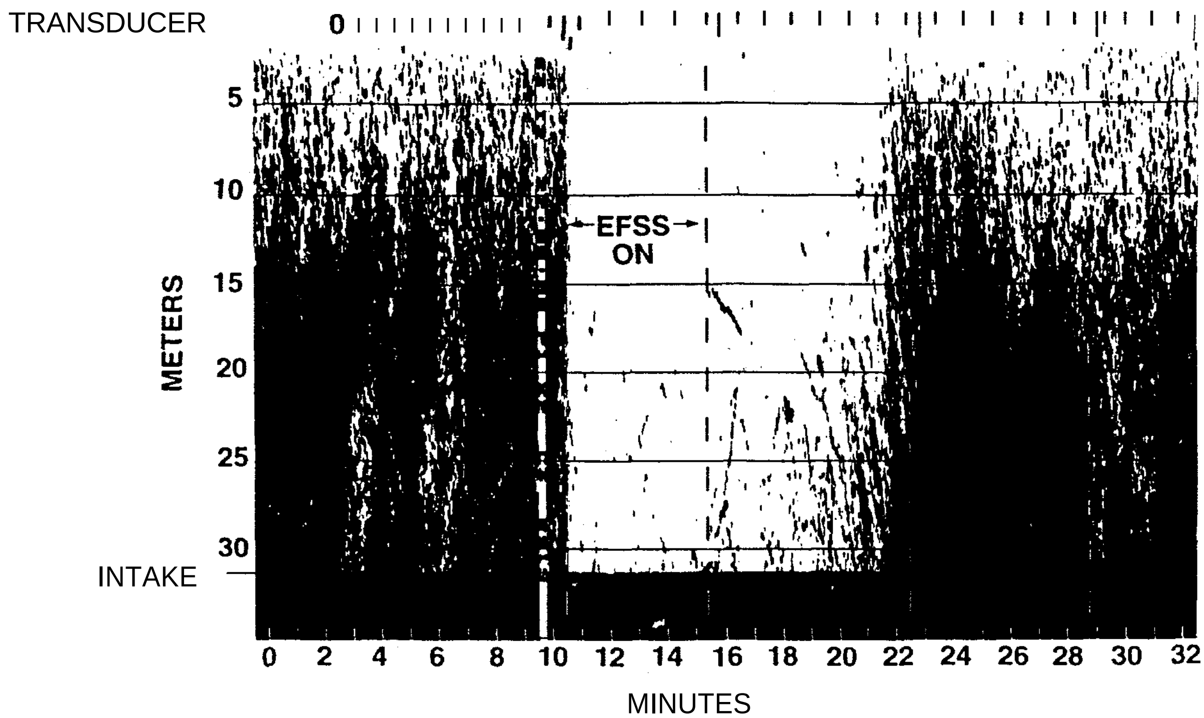


Figure 1

Echogram showing monitoring transducer at the top and the face of the intake at the bottom, with dark areas indicating a high density of fish.

Ultrasound/Infrasound FishStartle® Techniques: Herring, Shad, Pacific Salmonids

John Menezes
Sonalysts Inc.

I would like to focus on some of the engineering aspects and details of putting sound in the water. By way of introduction, I will tell you how we first got involved in acoustic technology. And I would like to address some of what I call the engineering considerations of deploying an acoustic system. As an example, I will talk about specific considerations as we applied them to Fitzpatrick, and also how we might address the problem on the Columbia River with the salmon. Basically, I've been doing work in sonar, submarine, and subsurface acoustics for about 20 years. In 1988, Dennis Dunning and ESEERCO were working on fish impingement and entrainment. They had mixed results with mechanical systems and wanted to know if they could do something electronic or state-of-the-art. And so the call trickled down to me, and we convinced them that we could do something. To make a long story short, I think we've made some significant progress. Since then we've applied our technology in a number of different situations, including fossil fuel, hydro, and an underwater construction project in Boston.

When you talk about Fish Startle@ or underwater acoustic systems, one of the things you might notice, from a system point of view, is that it's relativelv simple. You've got some electronics, power amplifiers, some transducers. You could run down to the local Radio Shack and pick up some of those. Except the problem, in this particular context of underwater acoustic svstems, is that these are relatively specialized technologies, and typically the people who are extremely knowledgeable about arrays and transducers may know little or nothing about power amplifiers. And so you wind up having to use a consortium of specialized ear, nose and throat doctors to address the problem.

For instance, when you talk about transducers, there's a number of different kinds of devices, e.g., magnetostrictive or piezoelectric, moving coil or fiberoptic, with different implications. You need to know the job at hand before you pick which path you want to go down. A lot of these experiments have been done using single elements, and even in a situation where we had a large number of them deployed at Fitzpatrick. You could call that an array, but some acoustic considerations and the spacing of those elements relative to tht frequency would determine the performance of that array.

We've had successful demonstrations at a number of different sites. Dennis Dunning referred to the first one at Fitzpatrick. We have done one at a hydroelectric facility on the Connecticut River in Vernon, Vermont, with American shad. And I will show you a little detail about the Boston Harbor effort. For those of you unfamiliar with the Boston Harbor problem, they were putting in a third harbor tunnel and had to do some underwater blasting. The construction permits allowed for blasting only during certain periods of the year, and not during spawning periods. One delay led to another, they needed to continue to blast, and it was the spawning period. So they would have faced a 3-4 month moratorium; and for a $5 billion project, somebody would have to pay for that. So they contacted us to see if we could keep the fish out while they were doing the underwater blasting. And we came up with a novel solution that allowed them to continue the project and also resulted in the saving of a lot of alewives.

These are some of the steps I consider necessary to developing a field-deployable system (Figure 1). First, we obviously have to identify what kind of sound elicits the desired response. Do we want to exclude the fish? Do we want to elicit a startle response? What is the response we're looking for? We also need to look at site-specific characteristics, because, as I'm sure you know, every site is different. Once we have knowledge of the specific site, we really need to apply acoustic design and modeling efforts to determine the optimum hardware-deployment characterization. Clearly there is a cost trade-off here in terms of redundancy, performance, and cost. Once it is installed and the system is effective, the plant operators will want to make sure that it's reliable, that it's maintainable, and hopefully with as little extra effort as necessary.

In terms of identifying which sound is most effective (Figure 2), I'll leave it to the biologists to come up with a shopping list or a focused approach to identifying the frequencies or kinds of sounds you want to pursue. That's important not only to get an effective result fromtesting, but because the frequencies you pick will determine what kind of transducers or electronics you pick for the demonstration, which will ultimately drive the cost of the demonstration. Once you've selected those and done some small-scale testing, you need to upscale it to a more effective large-scale test and ultimately generate a list of requirements for a field demonstration.

When I talk about site-specific characteristics (Figure 3), I'm concerned about things dealing with background noise, and I'll show you some examples of that. What kind of source level or power level do we need to put into the water? And should the signal be steady-state, i.e., it goes on and stays on, or should it be pulsed, or on and off at certain intervals? And then we need to look at the bathymetric data, because that will affect how the sound is propagated through the water.

I understand that a lot of people are talking about particle displacement and particle velocities and accelerations. And if you are going to buy an acoustic device – a transducer, a projector – it will be characterized by a sound-pressure or sound-source level. The point 1 want to make here is that the source level is proportional to the acoustic power; it's not the same as the power that's consumed coming off the outlet (Figure 4). There is an efficiency term in the conversion of electrical energy to acoustic energy, and you would need to add another term in this equation to account for that. But I think the important message is that the costs will be proportional to the power needed.

One other point to remember is that sound pressure is not a linear scale that goes on and on and on, up. There is a phenomenon known as cavitation that is really the rupture of the water caused by negative pressure gradients. If you exceed the negative pressure that the water can support, you will wind up with cavitation, and that creates a number of problems. From a system point of view, it will probably cause devices to become unloaded and mechanicallv tear themselves apart. You will notice this by the pitting on the surface of the transducers. But there are ways to reduce cavitation, by increasing the frequency and also decreasing the pulse length and/or the depth of the transducer.

Another item that we talked about was competing against background noise (Figure 5). I don't know what kind of noise you'd expect in the Columbia River, but I've dealt with this a lot in the open ocean. This shows a number of important points here. First, we're plotting spectrum level, or you can think of an example, due to amplitude as a function of frequency, and they are called sea states. Think of sea state 0 as calm, flat seas, no wind. And think of sea state 6 as 16-20 ft waves, wind speed that's causing white caps, and in general the noise level would go up. Another thing you'll notice as we go lower in frequency, is that the noise level goes up. So if the general trend is to suggest that to solve the salmon problem, you have to go lower in the frequency. I think you can see that we're competing against the higher level of background noise, things that we can't eliminate that's part of the environment, we are going to have to figure out how to deal with that. Because whatever signal that we put into the water to have some effect on fish behavior will have to compete against the higher background noise. And lots of different things affect those curves. For instance, rain in the river can increase those curves by almost 30 dB.

Taking another look at some of the site-specific characteristics (Figure 6), I like to look at the intake structure. For instance, Dennis Dunning's intake at Fitzpatrick is offshore and was quite different from the one at Vernon on the Connecticut River. You have to look at the trash-rack design. How and where the transducers are mounted is a dilemma for the maintenance people who don't want to put them there because of implications for trash removal and other characteristics. Once the biologist and the program people define the behavioral response (Figure 7), we have to establish the exclusion or guiding zones, and then develop an acoustic system accordingly.

As I mentioned before, in the Boston Harbor situation, there was a shot line (Figure 8). They had a large drilling rig that they would pull into position, and they would drill a number of holes in the bedrock in Boston Harbor. They would put -3000 pounds of explosives into these holes and then they would call us in. We had a portable fish-deterrence system mounted on the back of a small boat and we would then go up and down the shot line when they had cleared everyone back, including themselves. We would do this for -15-20 minutes, thev would give an 'all clear', and then the explosives would be detonated. And that worked pretty well. There were several advantages. Number one, we didn't have to keep the system on for the entire period. It allowed pretty much the upstream sporting migration to go on uninterrupted.

Figure 9 is a plan view of the Vernon situation, where the water flow was coming downriver this way to the high side of the dam. They had put in a 4-ft diameter fish-bypass pipe up near the surface that was supposed to encourage the American shad to go down. Unfortunately, when they got in here, they would just play around, swim back and forth, back and forth, and they would never leave town. So we wound up putting a transducer on opposite sides of the dam, and then timed the pulses from this source or that source so we could basically ping-pong the fish back and forth, trying to keep them in front of the fish bypass pipe. And when they were ensonified, they definitely didn't like the sound and they decided to take the bypass pipe.

Relative to designing the acoustic arrays, these are some of the parameters (Figure 10) I consider important. In the Boston situation, we took five directional transducers and mounted them off the transom of the boat. Having five of them gave us a large vertical coverage and a full 360" coverage.

I'd like to spend a few minutes talking about beam patterns (Figure 11) which applies to transducers whether they are in the receive mode or in the transmit mode. If you take an omnidirectional hydrophone, that is, equally sensitive from whatever bearing you are looking at, and you put it into an array or a structure, chances are you'll-have some degradation so it will no longer be uniform. That's what I've tried to show here with the yellow shading. Now, if we take a number of those elements and spaced them so they were less than half a wavelength apart, you get some benefits out of that. One is that you have what is called the 'rate of gain', where the signal-to-noise ratio on the output is significantly improved over the signal-to-noise ratio of an individual hydrophone at the input. The other advantage is that it gives you a much narrower beam so that you focus energy or a reception of energy. And if you have a number of these elements (Figure 12), you can apply delays and create multiple beams simultaneously. By processing a number of different elements, currently you can wind up with a multi-beam system. This is a simplified block diagram which you can use to either transmit or receive. But if we walked through it for a moment, on the receiving end, and you had hydrophones attached to each of these points at the top, sound would come down, hit those signals, hit those hydrophones, and travel through an amplifier, with some gain associated with each of those. And we can apply different gains to those, if you want to shape the beam for some reason.

The next thing we would do is apply some time delay to each of those elements. By staggering the delay correctly and then summing all of those elements, you wind up with an improved signal-to-noise ratio. If you wanted to use this to transmit, it has some advantages, too. One of which, except we would have to run it backwards – not literally backwards, you can't take the electronics, where the input was, and stick the output, vice versa. But if you think of this as the transmitter, you would have an electrical signal generated here, you would go through some delays to the individual elements, apply some gain to it, and ultimately to a power amplifier and the transducer. That would allow you to steer the energy around if you wanted to concentrate it in one area. The other important benefit is that it would allow you to increase the source level beyond what you get from a single element and beat the cavitation problem.

One of the other benefits of using this beam-forming technique on the receiver side of things is that you can sum these and split them into right and left halves, and then sum them, subtract differences, and come up with beam steering. So you can determine bearing from the source. If you don't need the array of gain, there is another technique of computing bearings from a fewer number of elements. And here I've tried to show what's called a 'progressive array technique'. We use a sparse element array, but we have hydrophone 1, 2, 3 and 4. And if we arrange them such that the difference between H-l and H-2 is less than half a wavelength, then we compute some jump ratios from H-l to H-3 and H-l to H-4. If you look at the signals between H-l and H-2, you can compute a correlation function, and the function will be at a peak where the bearing or target is. The problem with doing that between H-l and H-2 when you have a short distance between them is that, although you get an unambiguous bearing, it's very coarse. But you can use that to find the point and compute another, based on the jump ratio, in this case, 3. You would say, okay, I'll come over here to the third one, and I know this is a little more accurate, but if I only had H-l to H-3, I wouldn't know whether it was this peak, that peak, or that peak. But by using this pointer to say where it should be, you then improve the bearing resolution of what the target would be. If you do that a third time, you get a more accurate bearing.

I think the important point is that this allows you to compute bearings to lower frequencies with a fewer number of elements, and so it might be something you would want to consider. The implementation details are now such that you suddenly have to come up with some digital signal processing and you have to write some algorithms to compute the bearing, given that input; and that's not a trivial task.

I will blast through a few more items here. Some people have talked about transmission loss (Figure 13). One of the things you will see here on this 20 log R curve is that until you get above higher frequencies, you'll see some more absorption occurring. I believe that the typical sound-velocity profiles (Figure 14) were discussed in some detail by a number of different presenters. The point I would like to make is that I would expect to see a fairly steep thermal climb on certain occasions.

One of the differences you'll see from various people who are putting fish-deterrence systems in the water is in the signals (Figure 15). I would like to talk a little about those right now, because they have implications for system details and ultimately for cost. You can look at different kinds of signals here (Figure 16). For instance, this is a well-behaved sinusoidal tone and this is some noise. From a spectral point of view, noise has a much wider band width (Figure 17). We can either go pulsing tones or pulsing noise, and this is just the envelope of the pulses, or we can go continuous. That has implications in terms of the power supply and the power amplifier that you select. The other thing, relative to noise, is a quantity called 'peak to RMS value' that again has some implications for the ability of the power supply to support your function. This, again, has system implications because it has a fairly wide band-width signal that will place more demands on your power amplifier. You can think of it as the area under the curve. So if you have a relatively narrow signal, but very high amplitude and narrow frequency, the area is less than the area under this curve and therefore would presumably be easier to produce. I will let you read the installation details for yourself (Figure 18).

From a reliability and maintenance standpoint, you have to deal with Mother Nature, e.g., debris loading, ice, etc. (Figure 19). In the Fitzpatrick situation, we tested a number of different things, and I'll go into those rather briefly (Figure 20). One other major point relative to this figure that Dennis showed before is when you're dealing with 125 kHz and you have to get out here, that's probably about 700 or 800 ft as the crow flies. And if you have to pull it over here, you had to believe we had 1300 ft of cable. Anvone who's trying to drive 1300 ft of cable at 125 kHz will find out in pretty short order that the cable acts like a transmission line and not like a cable. So you will have to do some tuning to ensure that the power goes through the transducers and doesn't get consumed by the cable (Figure 21). Dennis showed you the transducers and the mounting of the different types of transducers there.

One point I would like to make in terms of deployment is that the advantage of these directional transducers is that they can in fact produce a higher source level than the wide-beam ones (Figure 22). But as you can see, the narrow-beam ones are not very effective at close range because you can see there are gaps in the coverage here. So we've developed what 1 call this 'layered defense' of one set of transducers to provide a far-field deterrence and another one near-field. And that also provided some redundancies, so that if you lost one transducer, you didn't necessarily open up a door for the fish to go through.

Getting down to the question of what you going to do for salmonids (Figures 23 & 24). I think that the deterrence system we have used for clupeids is not going to be the same for salmonids, and I'm not sure that the hardware and system-implementation issues are necessarily directly applicable either. 1 do think that the salmon problem is a lot more difficult, by an order of magnitude, than the other problems (Figure 25). I think you're going to need a team approach, with a core group of biologists, engineers of different expertise, mathematicians, computer modelers, and regulators and managers to form this critical team and keep that team focused in pursuing some identifiable milestones and also to maintain a corporate memory and the interdisciplinary approach that will be required. I think people are going to have to look at other people's comments. And I think we're all trying to get to the same place, i.e., that the fish continue on their merry way. Thank you.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- IDENTIFICATION OF SOUND WHICH ELICITS THE DESIRED BEHAVIORAL RESPONSE
- DETERMINE SITE SPECIFIC CHARACTERISTICS
- DEFINE DESIRED BEHAVIORAL RESPONSE
- DESIGN ACOUSTIC TRANSDUCERS/ARRAY
- SIGNAL GENERATION, DESIGN AND IMPLEMENTATION
- INSTALLATION DESIGN
- RELIABILITY, SAFETY AND MAINTENANCE

Figure 1
Considerations for developing a sound-deterrence system

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- IDENTIFICATION OF SOUND WHICH ELICITS THE DESIRED BEHAVIORAL RESPONSE
  - » RESEARCH INTO MORPHOLOGY OF SPECIES
  - » SELECTION OF CANDIDATE FREQUENCIES AND TEST SIGNALS
  - » SELECTION OF SMALL SCALE ACOUSTIC DEVICES
  - » CONDUCT IN-SITU ACOUSTIC TESTS (CAGE TESTS)
  - » ANALYSIS OF RESULTS
  - » REFINEMENT OF TEST PROTOCOL; RETEST
  - » DEFINE ACOUSTIC REQUIREMENTS FOR FIELD DEMONSTRATION

Figure 2
Identification of sound which elicits the desired behavioral response.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- DETERMINE SITE SPECIFIC CHARACTERISTICS

  » BACKGROUND ACOUSTICS
  FREQUENCY SPECTRUM
  SOURCE LEVEL & LOCATION
  STEADY STATE VS. TRANSIENT

  » BATHYMETRIC DATA
  SEASONAL WATER LEVEL VARIATION
  BOTTOM CONTOUR AND TYPE
  SOUND VELOCITY PROFILE

Figure 3
Determining site-specific characteristics.

MKS UNITS

ACOUSTIC PRESSURE: 1 MICRONEWTON PER SQUARE METER, OR MICROPASCAL; ABBREVIATED μPa

$$SL = 171.5 + 10 \log P$$

P = TOTAL *ACOUSTIC* POWER

Figure 4
Meter-kilogram-second (MKS) units.

TYPICAL AMBIENT NOISE SPECTRA

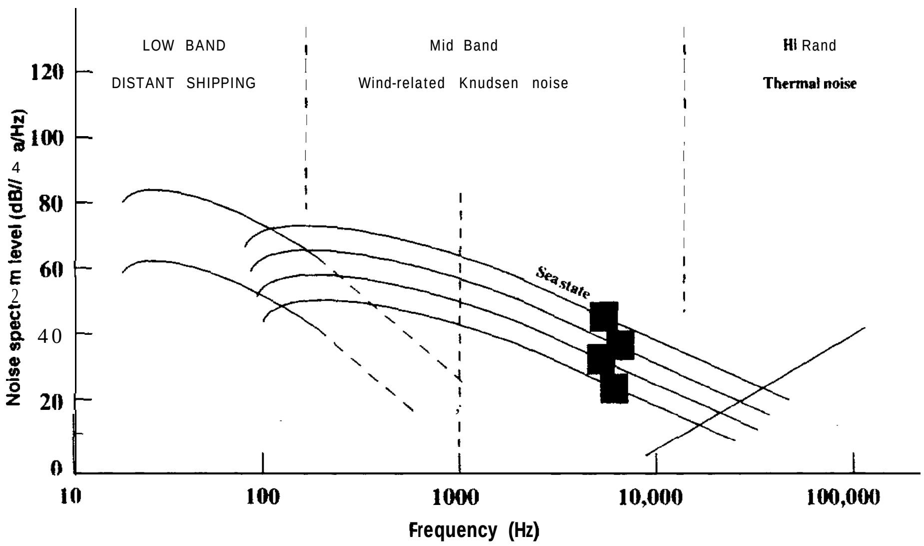


Figure 5
Typical ambient noise spectra.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- DETERMINE SITE SPECIFIC CHARACTERISTICS (CONT'D)

  » INTAKE STRUCTURE
  - SIZE AND LOCATION OF PROMINENT FEATURES
  - TRASH RACK DESIGN
  - NUMBER OF TURBINES AND OPERATING MODES
  - LOCATION OF FISH BY-PASS SYSTEMS

  » WATER FLOW CHARACTERISTICS
  - FLOW VELOCITY PROFILE
  - EFFECTS DUE TO CHANGES IN PLANT OPERATION
  - TURBULENT FLOW CONDITIONS

Figure 6
Determining site-specific characteristics (continued).

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- DEFINE DESIRED BEHAVIORAL RESPONSE
  - » ESTABLISH EXCLUSION ZONES (JAF)
  - » MAINTAIN SAFE DISTANCE BETWEEN MIGRATING FISH AND DANGER AREAS (BOSTON HARBOR)
  - » GUIDANCE TO INCREASE USE OF FISH BY-PASS TECHNOLOGIES (VERNON)

Figure 7
Defining desired behavioral response.

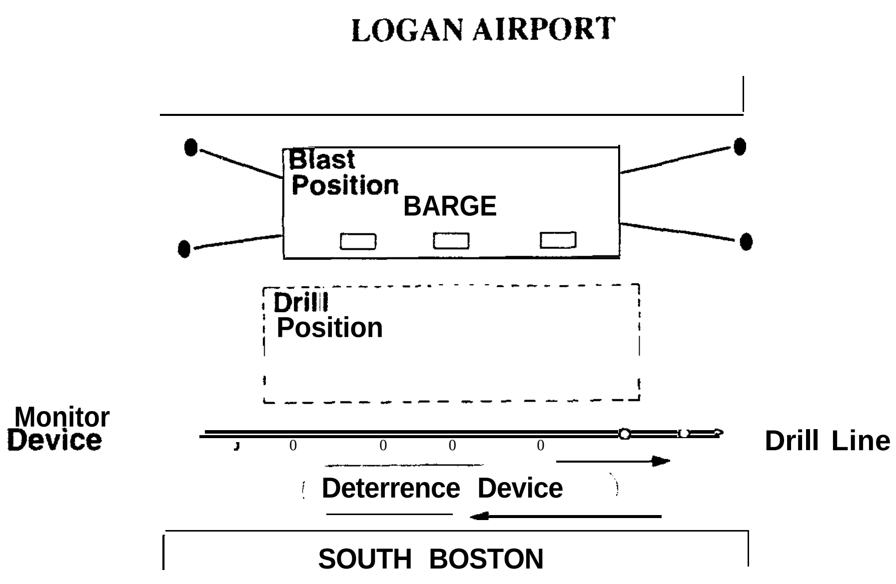


Figure 8
Underwater acoustic system in Boston Harbor.

VERNON HYDROELECTRIC DEMONSTRATION

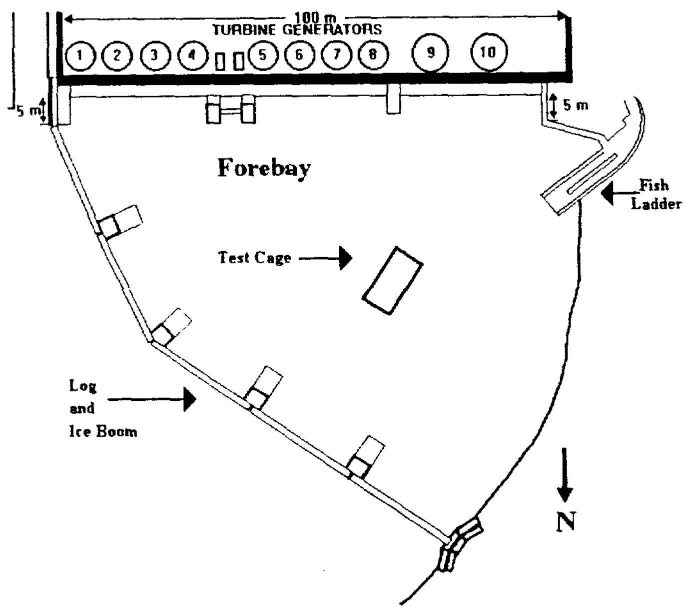


Figure 9
Underwater acoustic system at Vernon Hydroelectric facility.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- DESIGN ACOUSTIC TRANSDUCERS/ARRAY
  - » ACOUSTIC MODELING
    - DEVICE BEAMPATTERNS
    - PROPAGATION LOSS
    - SOUND VELOCITY PROFILING
    - LLOYDS MIRROR EFFECT
  - » LAYER ACOUSTIC SOURCES TO EXPLOIT BEAMPATTERN OVERLAP TO INCREASE COVERAGE, INCREASE RELIABILITY

Figure 10
Designing acoustic transducers and arrays.

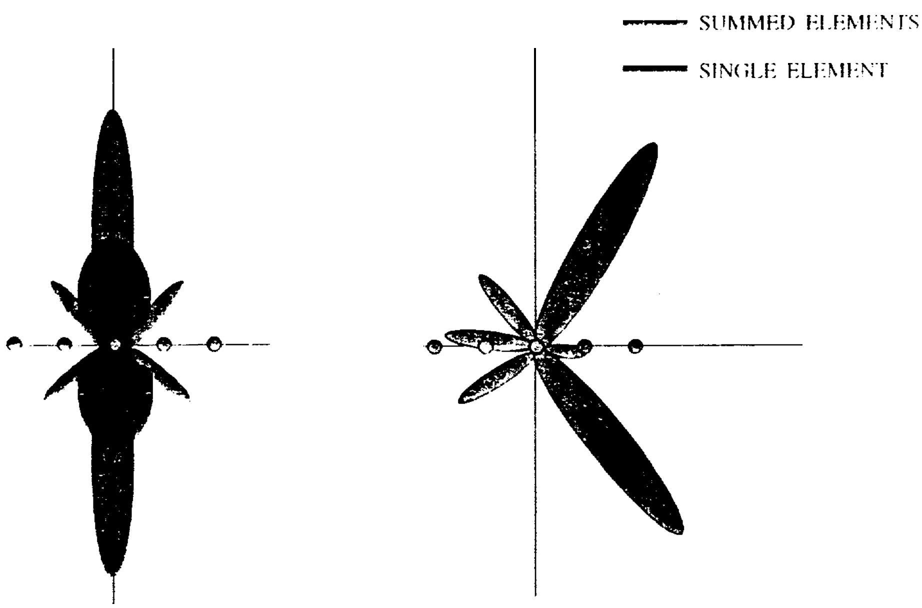


Figure 11
Beam patterns.

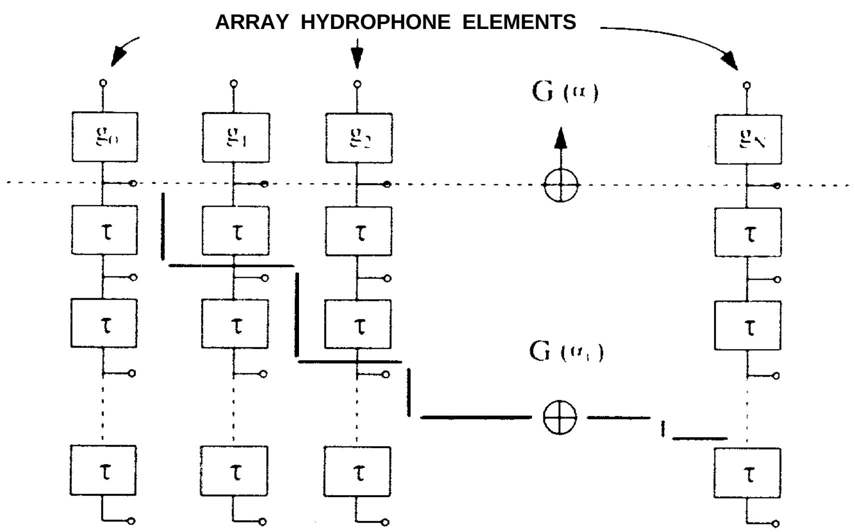


Figure 12
Beam forming.

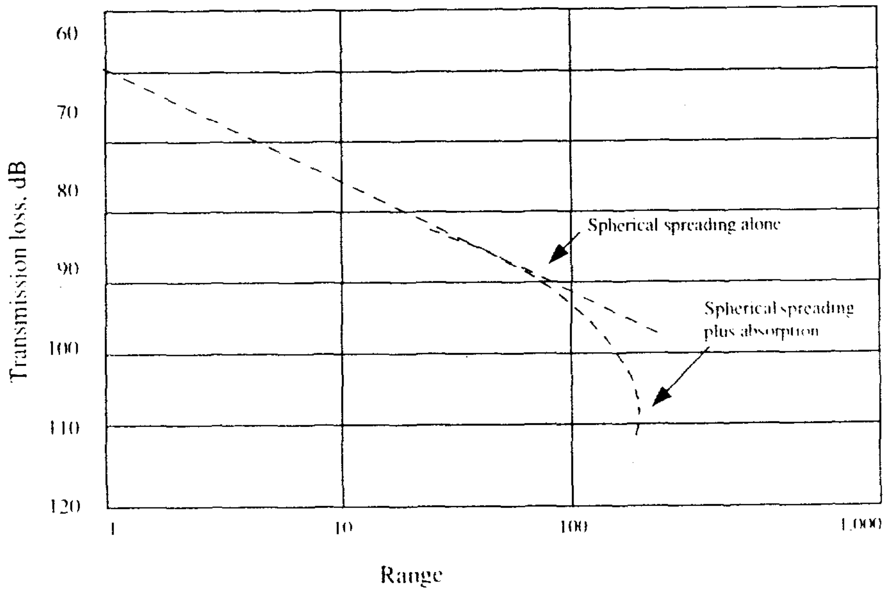


Figure 13
Transmission loss.

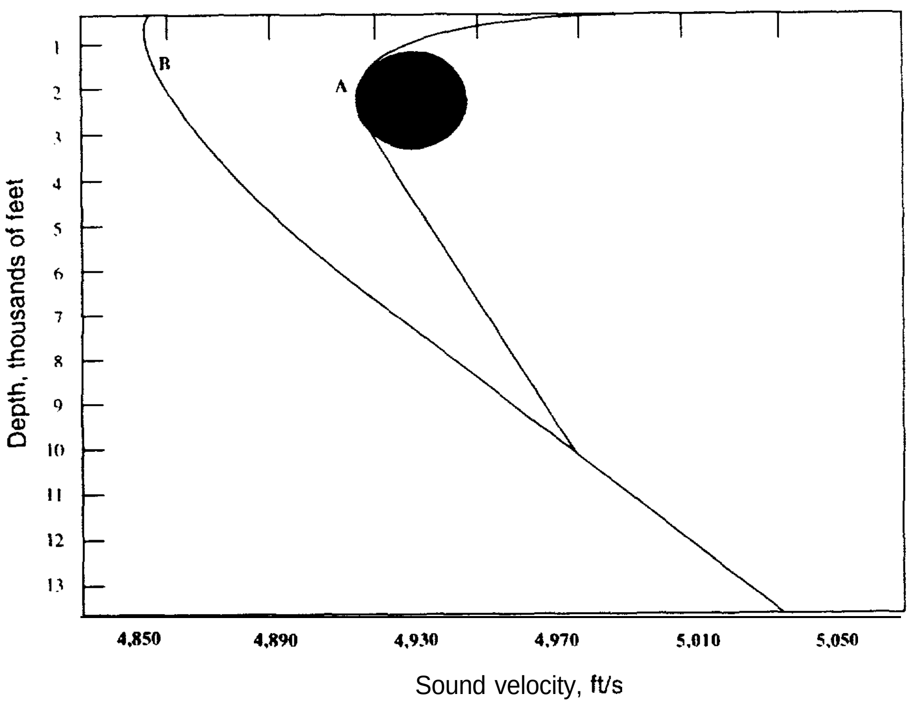


Figure 14
Typical sound-velocity profile.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- SIGNAL GENERATION, DESIGN AND IMPLEMENTATION

  » ESTABLISH SIGNAL CHARACTERISTICS

  TONES VS. NOISE
  PULSED VS. CONTINUOUS
  SWEEP RATE
  PULSE WIDTH
  RISE TIME

  » SIGNAL CONTROLLER

  » POWER AMPLIFIER DESIGN

  TRANSDUCER LOAD IMPEDANCE MATCHING/TUNING

  » SIGNAL CABLE CONSIDERATIONS

  RUGGEDIZED CONSTRUCTION
  UNDERWATER MATEABLE CONNECTORS
  ELECTRICAL CONSIDERATIONS

Figure 15
Signal generation: Design and implementation.

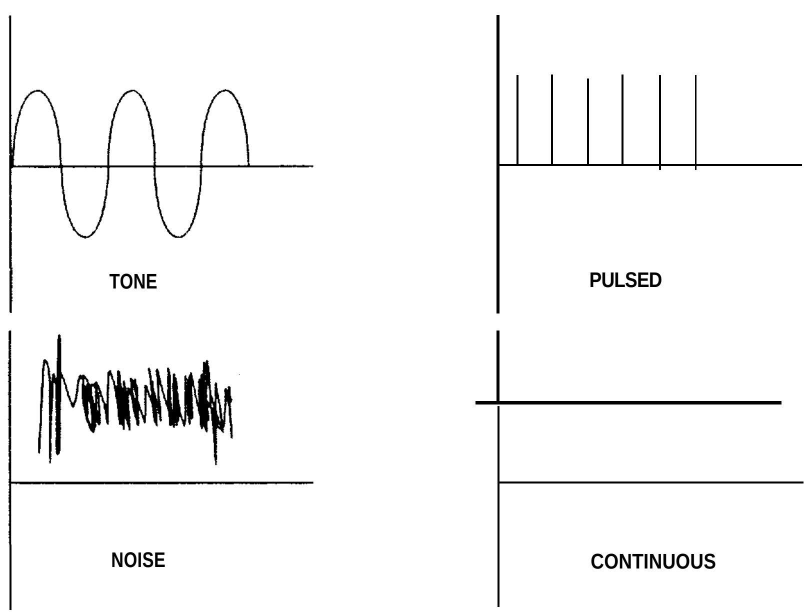


Figure 16
Signal characteristics.

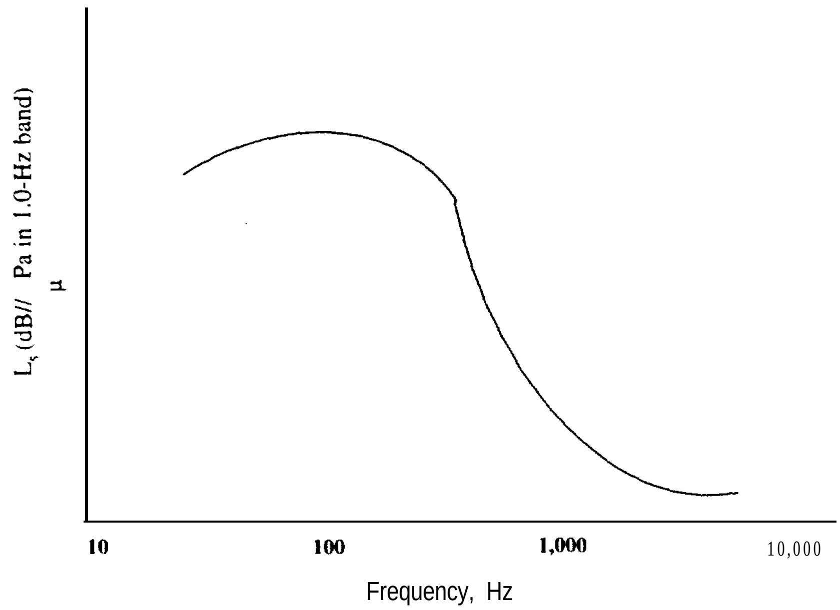


Figure 17
Spectral level of typical broadband acoustic signal

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- INSTALLATION DESIGN
  - TRANSDUCER MOUNTING OPTIONS
  - PERMANENT VS. SEASONAL INSTALLATION
  - TRANSDUCER ALIGNMENT AND CALIBRATION
  - PROTECTION FROM DEBRIS AND ICE LOADING
  - LOCATION OF SIGNAL CABLE
  - SITE POWER REQUIREMENTS

Figure 18
Considerations for installation design.

CONSIDERATIONS FOR THE DEVELOPMENT OF A SOUND DETERRENCE SYSTEM

- RELIABILITY, SAFETY AND MAINTENANCE

  » EASE OF TRANSDUCER ACCESSIBILITY FOR REPAIR/REPLACEMENT

  » SPARE SIGNAL CABLE

  » PROTECTION FROM PLANT MAINTENANCE EVOLUTIONS
  TRASH RACK CLEANING

  » AVOID OPERATION OF TRANSDUCERS AT LOW WATER LEVELS
  CAVITATION
  LOSS OF COOLING

  » AVOID ICE AND HEAVY DEBRIS LOADING

Figure 19
Reliability, safety, and maintenance of a sound-deterrence system.

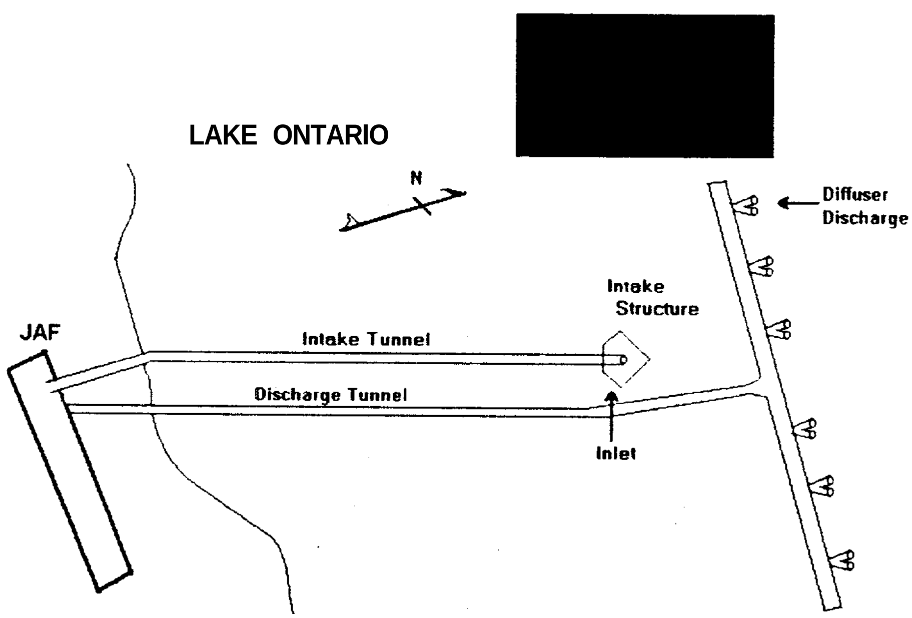


Figure 20
Plan view of Fitzpatrick Nuclear Generating Station, New York.

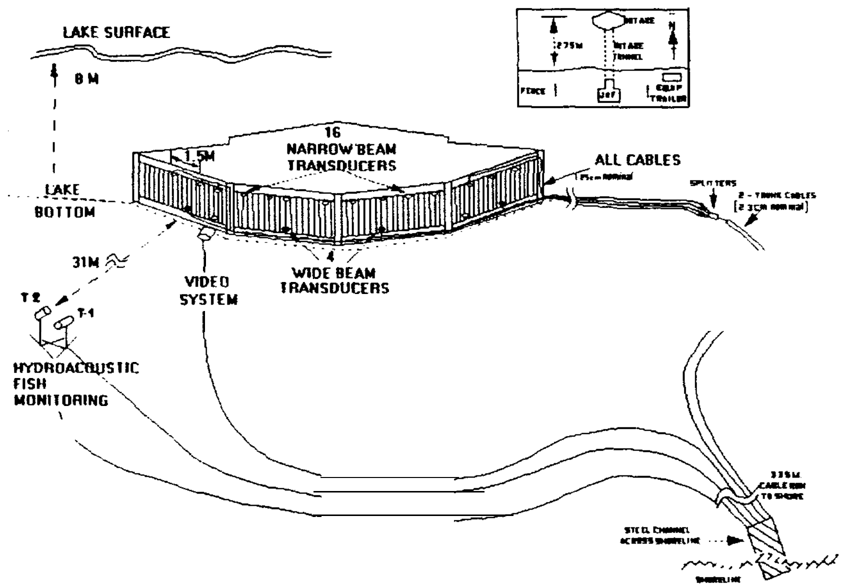


Figure 21
Intake structure of Fitzpatrick Nuclear Generating Station.

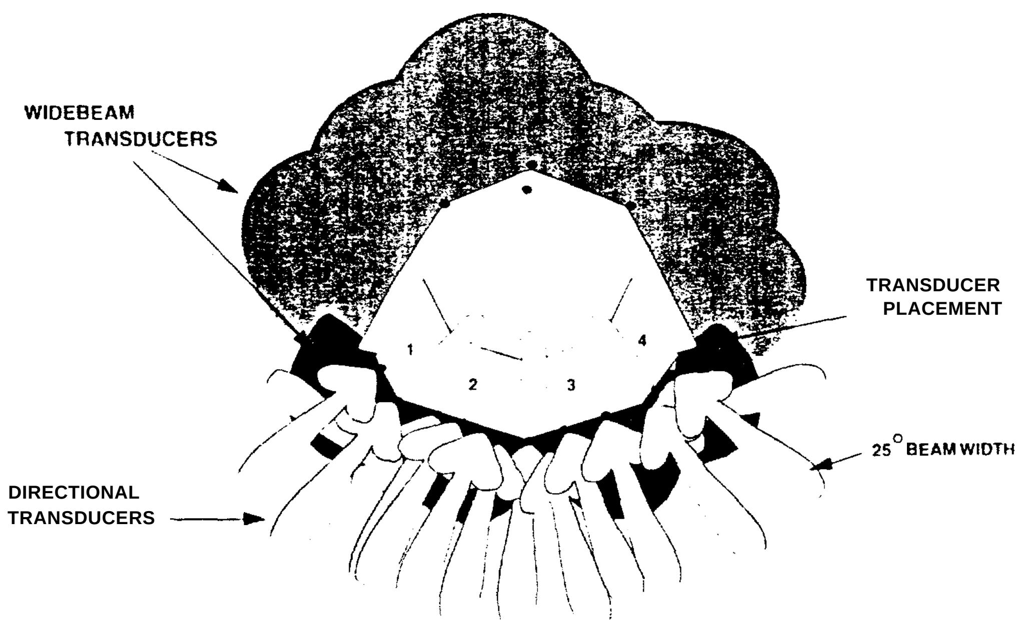


Figure 22
Acoustic layout of Fitzpatrick Nuclear Generating Station.

THE SALMONID SOLUTION

- PHASED APPROACH
  - » ESTABLISH GUIDELINES TO REDUCE SALMONID ENTRAINMENT
  - » DEVELOP A LONG TERM SCHEDULE WITH ACHIEVABLE MILESTONES
  - » MAINTAIN A "CRITICAL MASS" OF INTEGRATED TEAM
    - CORPORATE MEMORY
    - INTERDISCIPLINARY APPROACH
    - COMMIT RESOURCES FOR THE LONG TERM

Figure 23
The salmonid solution.

LEVERAGE RECENT SUCCESSES

- WEST COAST SALMONID ISSUE

  MANY UNIQUE ASPECTS...
  - » CLUPEID EXPERIENCES NOT DIRECTLY APPLICABLE
  - » DETERRENCE SYSTEM IS NOT DIRECTLY TRANSFERABLE
  - » TESTING PROTOCOL IS TRANSFERABLE
  - » ENGINEERING DETAILS MAY BE SIMILAR

Figure 24
Leveraging recent successes for the West Coast salmonid issue.

THE SALMONID SOLUTION

- TEAM APPROACH
  - » BIOLOGISTS
  - » ENGINEERS; ACOUSTIC, ELECTRICAL, SOFTWARE, MECHANICAL, AND HYDRAULIC
  - » SCIENTISTS; MATHEMATICS, PHYSICS, STATISTICS
  - » REGULATORS
  - » PROJECT MANAGERS

Figure 25
The salmonid solution (continued).

Ultrasound Deterrence: Blueback Herring at a Pumped Storage Facility in Georgia

Carl Schilt
Trotters Shoals Limnological Research Facility

Gene Ploskey
Army Engineer Waterways Experiment Station

MR. SCHILT: I'm Carl Schilt, and I work at the Richard B. Russell Dam on the Savannah River. I'm affiliated with John Nestler from the U.S. Army Engineer Waterways Experiment Station (WES). I'd like to say that it is such a privilege to be here, to listen to you folks whose work I have been reading all these years. I'd like to thank Tom Carlson and John Nestler for the opportunity to be here and meet these folks.

Russell is a dam on the upper Savannah River. It's sandwiched between a couple of other dams. It has eight Francis turbine units, four of which have pump-back capability. It passes a lot of water, -60,000 cfs during generation and 30,000 cfs during pumpback. Just downstream in the tailrace, there's a very popular sportfishery that consists primarily of hybrid bass and striped bass, which are part of a put-and-take fishery, which means the state government employees put the fish in there and citizens catch them. But what the sportfish eat is largely blueback herring, which makes blueback herring protection important, Here (Figure 1) is an aerial photo of Russell.

Russell has -140 ft of head, what we call a medium-head project. The spillway is on the right and the powerhouse is on the left. These little crescent-shaped alcoves each represent a turbine unit. There are eight units going across there. Figure 2 is from downstream, looking toward the dam. You see one, two, three, four generation-only units on the left of the powerhouse and four generation and pumpback units on the right. I suppose most people in the industry know what pumpback is. It turns out that it would be nice to make the water go uphill again so you could generate with it tomorrow, and it turns out that electricity is really a whole lot cheaper in the middle of the night instead of the middle of the day, so it is cost-effective to shove the water back uphill. Figure 3 shows that very thing happening. In the tailrace, the water on the downstream side is often -50 or60 ft deep, and in the forebay it's often 140 or 150 ft deep. But the penstock opening upstream is a lot bigger than the tailrace intake. So if you're shoving the same amount of water, the tailrace velocities are a lot greater and you're also drawing out of a smaller bucket.

The dam seems to be a fish magnet, maybe because of the cold, oxygen-rich water released during generation. So in the spring and summer especially, the fish come right up and put them-selves in harm's way. So here is the blueback herring story. You can't stock them like stripers and hybrids. They just don't lend themselves to that. They reproduce naturally here. I'm sure you know that they are an anadromous species, but in this case they are landlocked. They don't get as big as when they get to go to the ocean, but they do just fine. And there (slide) is a bunch of them. How big a bunch is hard to say, and there are efforts ongoing to find out. You may also know that, so far, only members of the genus *Alosa* seem to be sensitive to these very high tones, although there are some anecdotal reports of other saltwater fish responding. **But** so far it appears to be only *Alosa.* It's hard to screen out blueback herring. They're little and squishy; if they hit things like bar racks or screens, it doesn't do them much good; and if you put a small-enough screen on to stop blueback herring, you will stop leaves and sticks. So, those are the reasons you can't do more conventional things.

So in 1988 or 89, the first time I went there, we all did some experiments. They were admittedly brief and were all based on the notion that these very high tones affect the distributions of these fish. Which was actually discovered serendipitously by some folks, especially a guy named Al Menin who was a Bendix engineer and Boyd Kynard up in the Northeast, who found out that he seemed to be chasing American shad away with 161 kHz. So John Menezes brought down a low-frequency sound source and we had a Navy high-frequency source, an F41 transducer, and we did some experiments that are very similar in type to what Dennis Dunning discussed. This is where we did the experiments (Figure 4). There's some water here, and it's 3 or 4 or 5 m deep out in there, which is not very deep for low sounds. But if you've got a wavelength of 1.2 cm, which I think is correct for 120 kHz, that's pretty deep. And we had this net pen that we put some fish in and asked them what they thought of the sound. Here's a drawing **(Figure 5)** of the little shack that we had. The net pen was divided into four quadrants. At time T, you ask the question, how are the fish arrayed in those quadrants, and you estimate that 70% of the fish are in one quadrant, and 30% are in another, and the other quadrants are empty. So you come up with what John Nestler calls a decile distribution. It gives you a real coarse look at how the fish are arrayed in that environment. So that's how we looked at where the fish were.

Here is the real thing **(Figure 6)**, the pen on the right and buoys suspending a low-frequency source on the left. It was -50 feet away from the end of the pen. The pen was 20 x 4 x 4 ft. Here is the high-frequency source (Figure 7), much closer to the pen. The water was not very clear. You could see the fish as shadows against the white bottom of the pen. Fish were put in sometime before midnight. We did the experiments the next day, so they had some hours to acclimate. And Figure 8 gives a breakdown of the different things we tested. None of these were extensive, long-term tests. They were rather brief, but they were meant to point us in the right direction. In this time-series diagram (Figure 9), the sound source is at the top and bars indicate the distribution of blueback herring among quadrants 1–4 through time (left to right). In the 150-Hz test (bottom panel), fish stayed in the middle quadrants; at 120 Hz, fish moved away from the source; and the controls wandered around, ending back up near the source. So if you do a bunch of those over time, you can say, here's the wav the fish moved around during that time, in kind of a quantitative way. It's a rather crude m&hod, but it works.

So we looked at those differences and did something called a Ryan-Einot-Gabriel-Welsch multiple F range test (Figure 10). And all that does is clump these; it tells you which of the treatments were different. So if you do an ANOVA, it says something's different. And so this says, the only one that was different was what we call the high-frequency test. The 420-kHz test was high-frequency, too, of course. The amplitudes put out by the high-frequency sound were on the order of 190 dB//µPa. Prettv loud. So it turned out that the 120-kHz sounds in that very broad range were what seemed to do the trick. The lower frequencies that had seemed to maybe be useful for stripers and some other things didn't seem to do much of anything.

With a Navy F41 transducer, we could test for 110-140 kHz, and we did that, and it seemed like -120 or 130 kHz worked. So that's what we're using at Russell. Gene's going to tell you about what we're doing at Russell. Because it seems to me that we have to do these things in all these different stages. The dam manager needs something that works yesterday. So we have to -do these clinical trials. You find a solution that may work and then you make it work in this laboratory environment, but the rubber really meets the road in the tailrace. So we're constantly cutting those two things against each other, and schedules of course are terribly important. At 200 ft, we dragged the pen away and turned it on, and sure enough blueback herring still seemed to swim away. That's in the net pens. Gene will tell you about open-water testing. This is a cute **slide** (Figure 11) to remind me to tell you that we know that effective ultrasounds are two orders of magnitude higher than Per Enger thought these fish could hear. We're interested in that. We have no idea what the transduction mechanism is.

Figure 12 is an x-ray of a blueback herring, and these are the gas bladder, and next to the ears are the prootic amd pterotic bullae that are made of dense bone and full of air. And I have wondered, could that perhaps resonate? I don't know. But for some of you folks who know some acoustics, 16 of these fish averaged 2.2 mm diameter. There may be something interesting about the duty cycle that we're using. I hope to do some experiments in this enclosure (Figure 13), which is a little nicer than a net pen, to do some fine-tuning of our response evaluations.

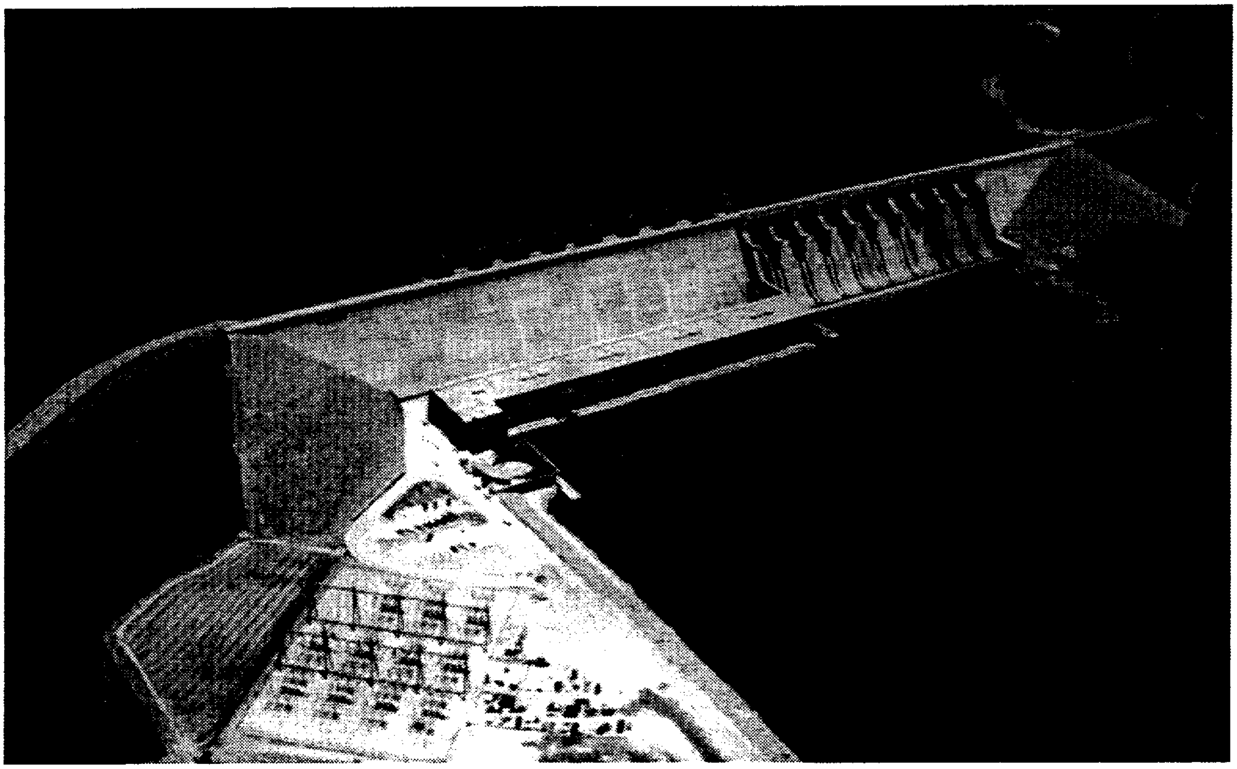
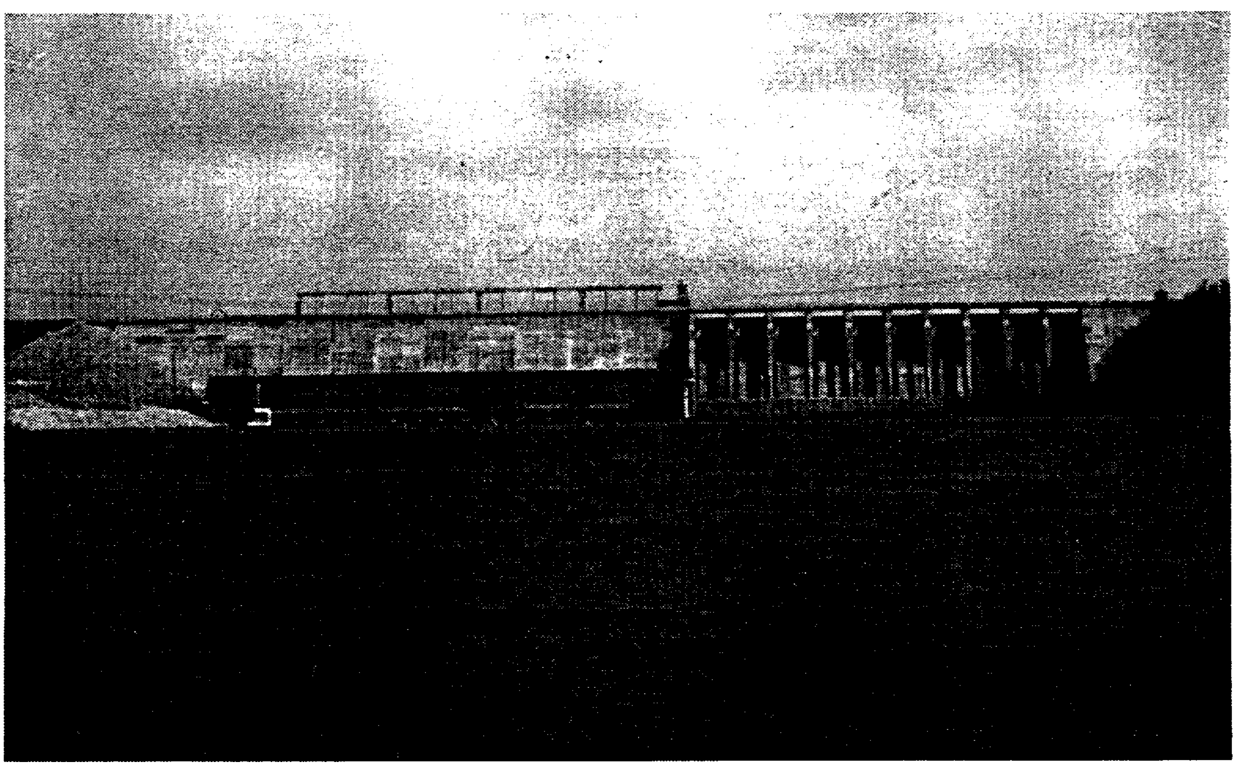


Figure 1



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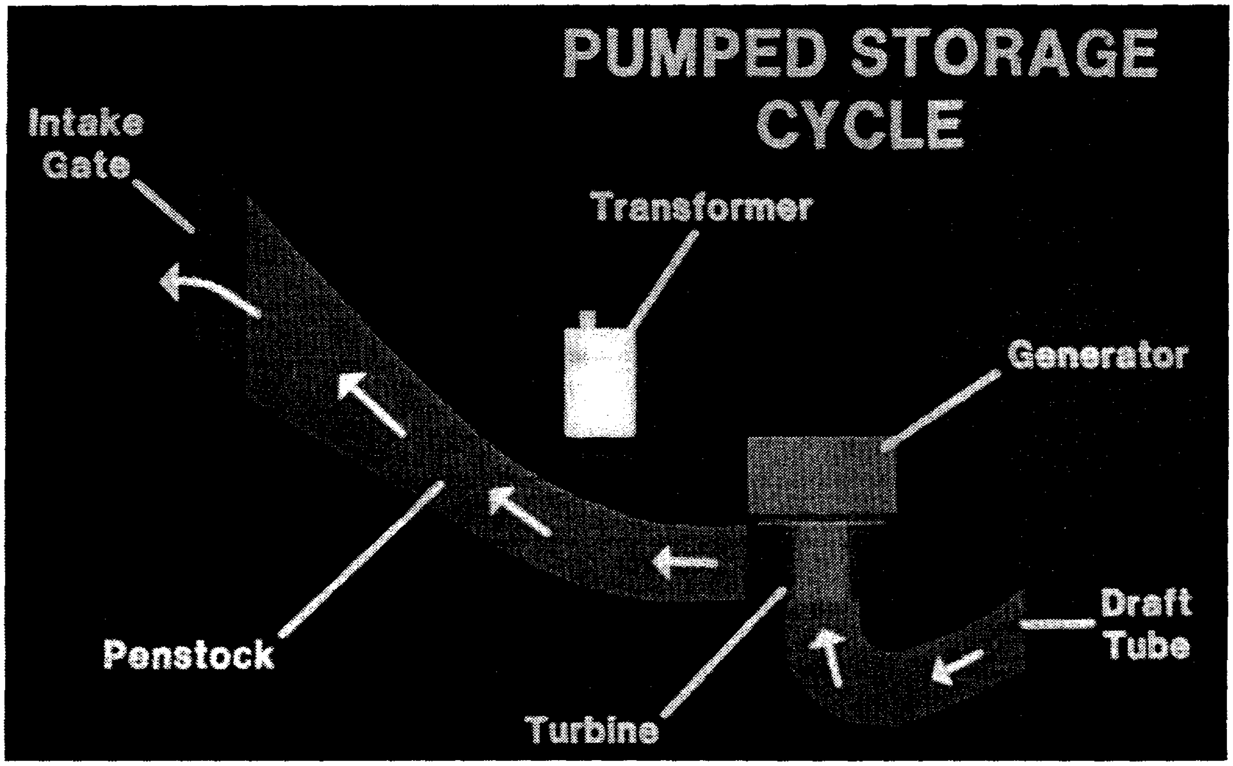

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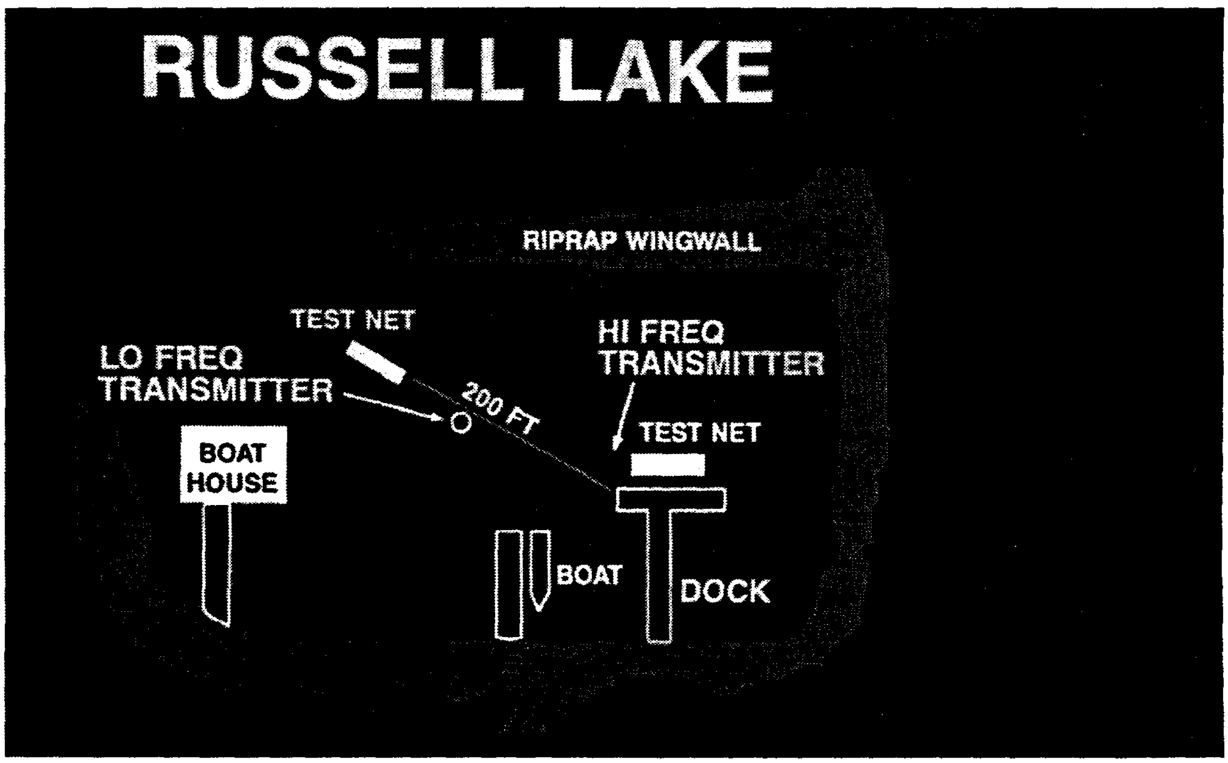

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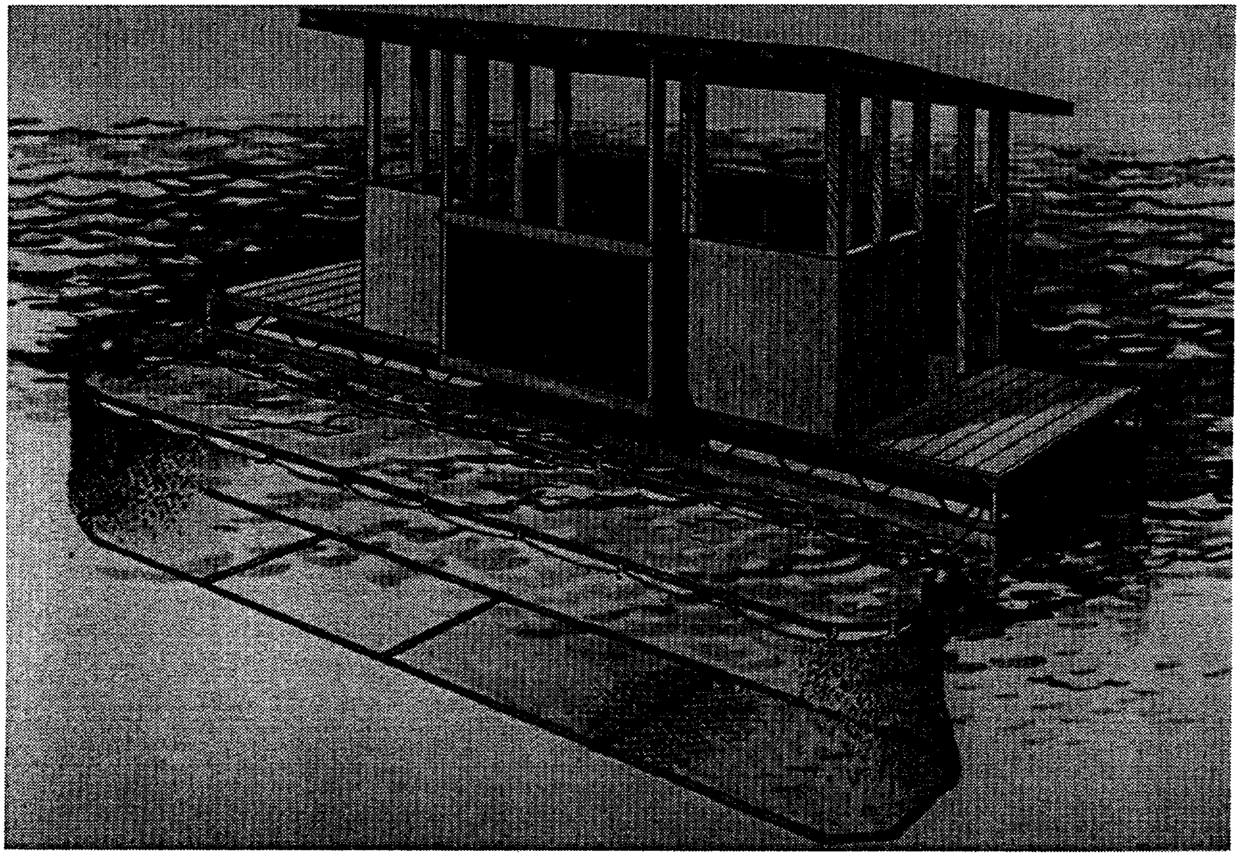

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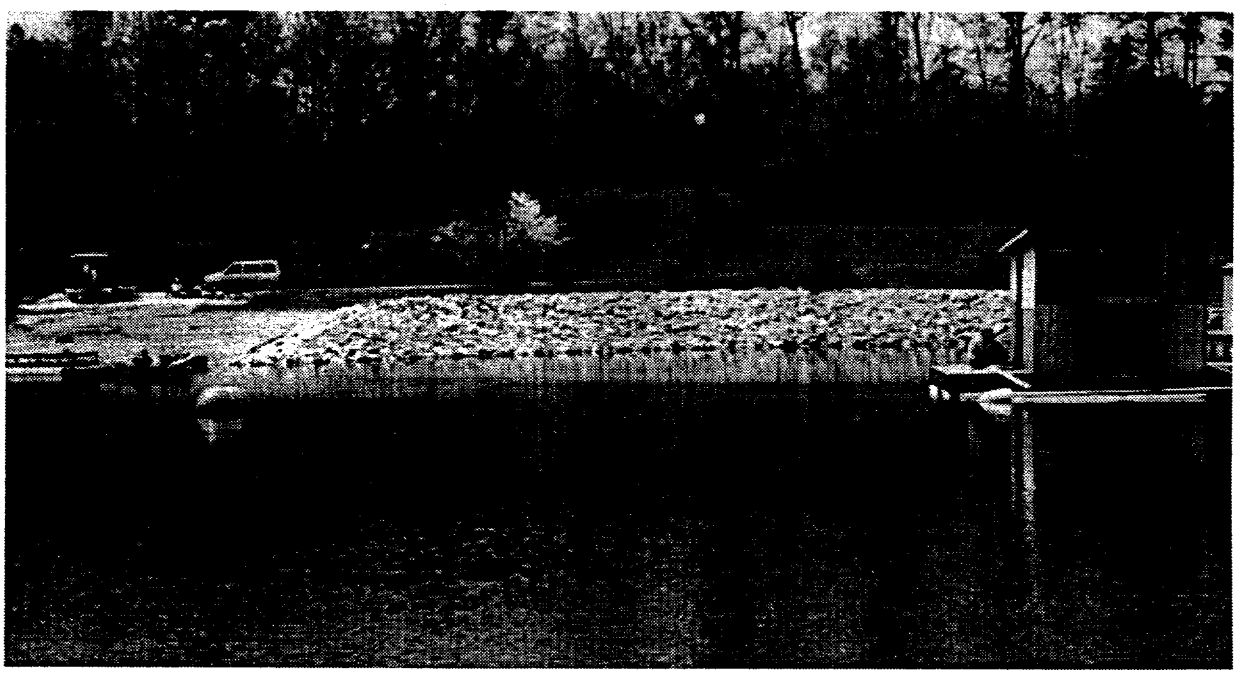


Figure 6

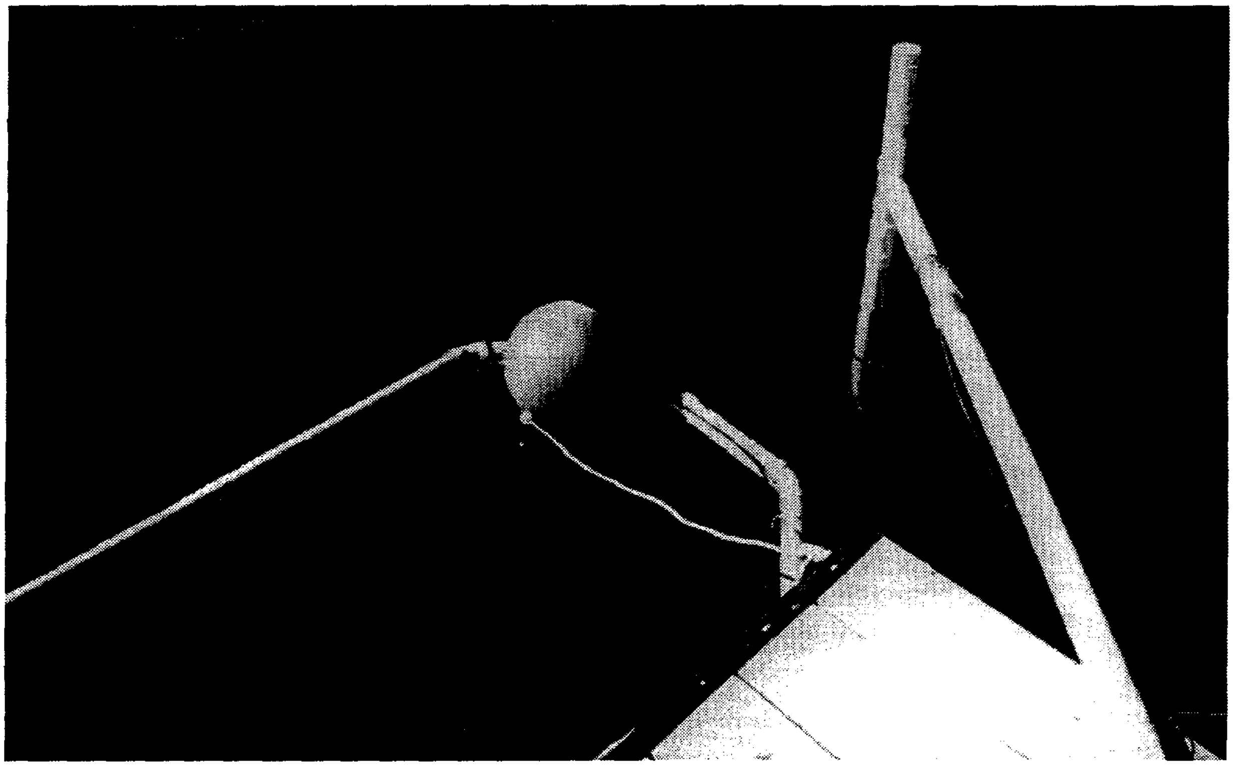


Figure 7

PHASE 1 LOW-FREQUENCY (UPPPER BLOCK) AND HIGH-FREQUENCY (LOWER BLOCK) SOUNDS TESTED FOR EFFECTS ON BLUEBACK HERRING

Sound	*SPL*	*Pulse Width*	*Pulse Wave Form*	*Interval*	*Duura tion*
80 kHz	191	Constant	Sine	Constant	1
80 kHz	191	200 MS	Sine	1 sec	1
100 kHz	198	Constant	Sine	Constant	1
100 kHz	198	200 MS	Sine	1 sec	1
110 kHz	199	200 Ms	Sine	1 sec	1
120 kHz	201	500 Ms	Sine	1 sec	1, 15
120 kHz	201	Constant	Sine	Constant	1, 15
130 kHz	204	200 MS	Sine	Constant	1
130 kHz	204	Constant	Sine	Constant	1
130 kHz	204	200 MS	Square	Constant	1
130 kHz	204	Constant	Square	Constant	1
140 kHz	206	Constant	Sine	Constant	1
140 kHz	206	200 MS	Sine	Constant	1
150 kHz	208	200 MS	Sine	Constant	1
150 kHz	208	Constant	Sine	Constant	1
420 Khs	200 watts	Constant	Sine	Constant	1

Figure 8

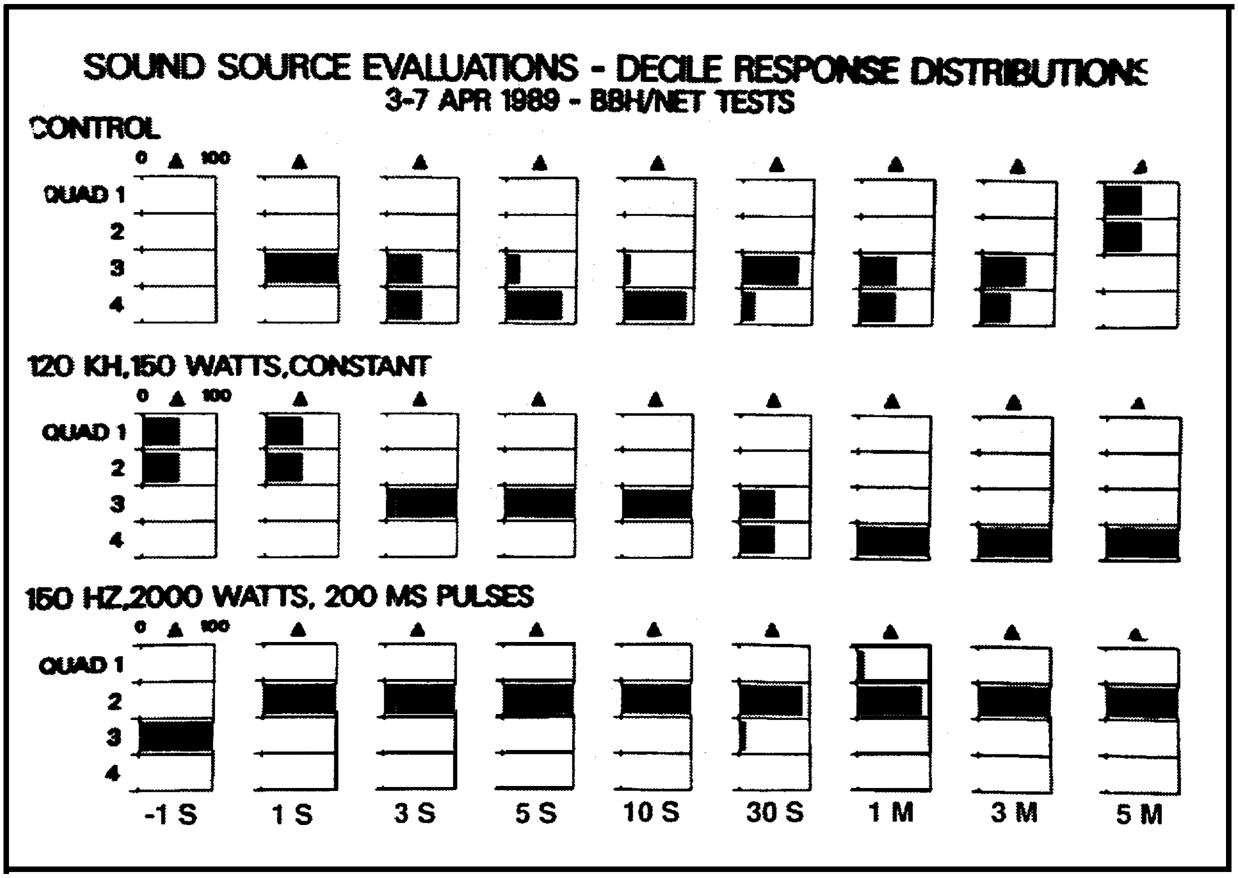


Figure 9

RESULTS OF RYAN-GABRIEL-WELCH MULTIPLE F (REGWF) RANGE TESTS ($\alpha = 0.05$)

REGWF Grouping	Mean	N	Test
A	0.7166	230	HIGH
B	0.22188	11	420 kHz
B	0.1093	83	LOW
B	0.0813	56	CONTROL

Figure 10

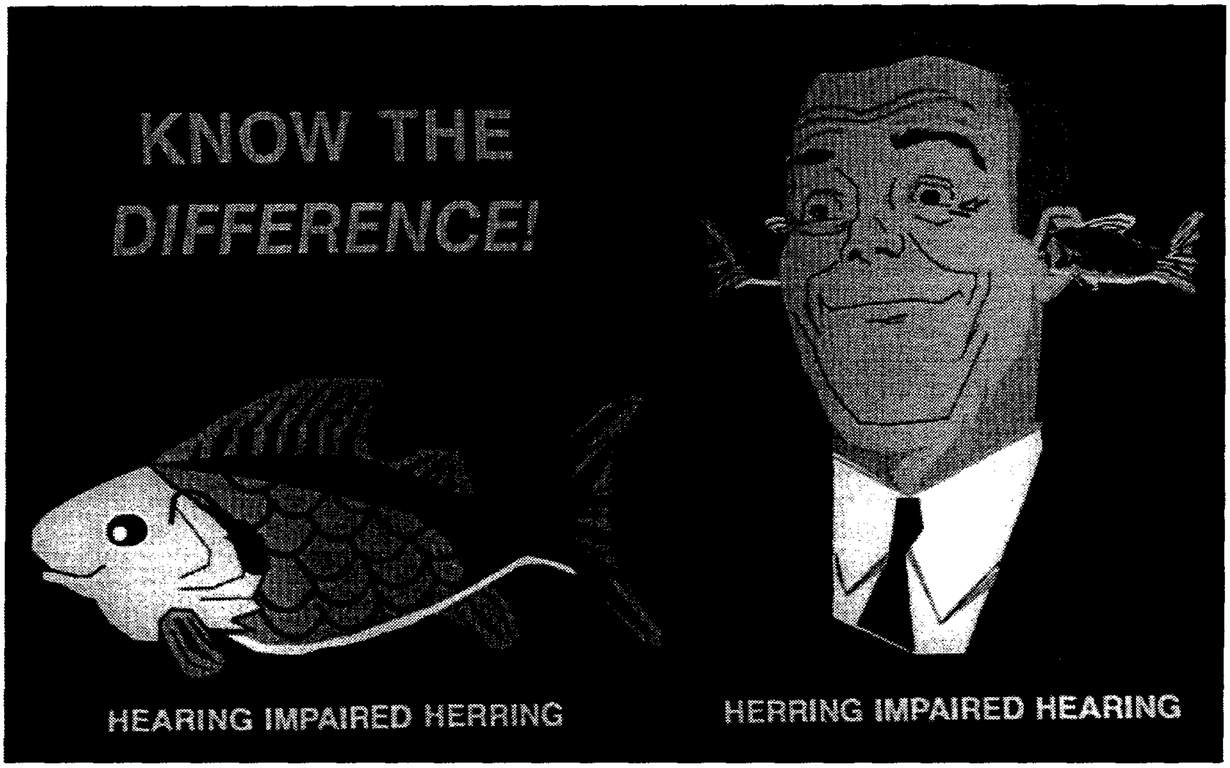


Figure 11

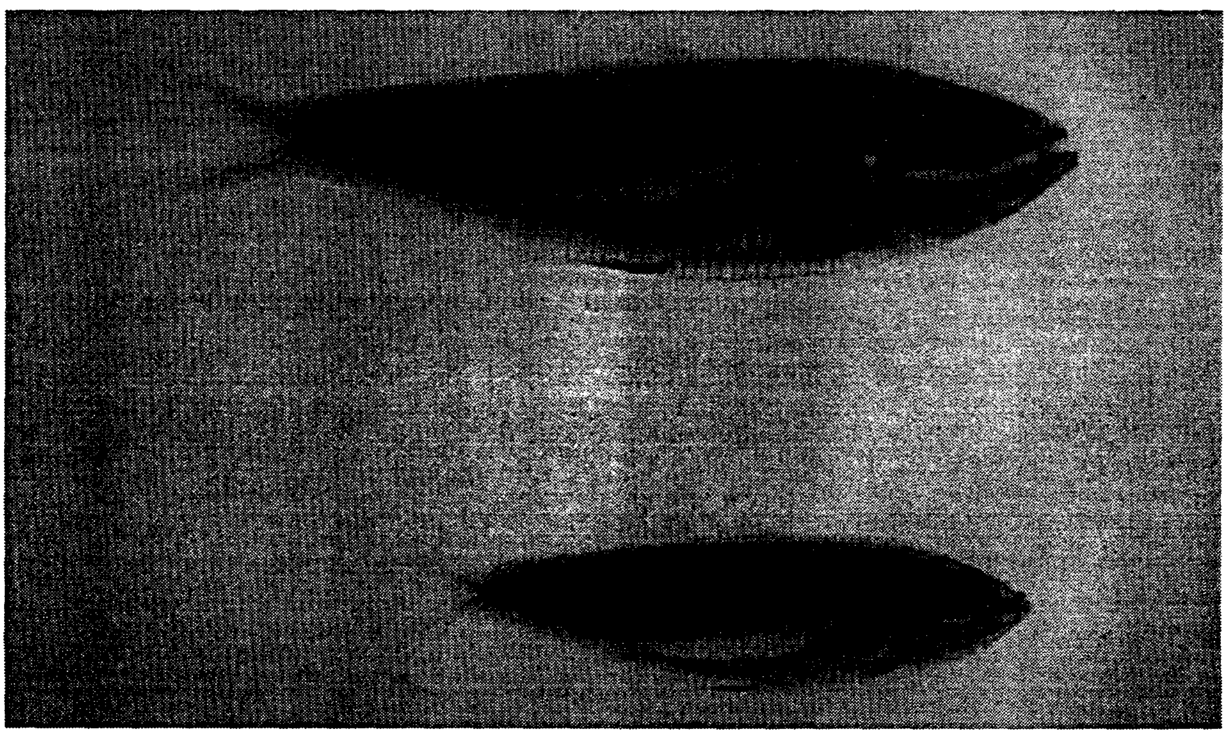


Figure 12

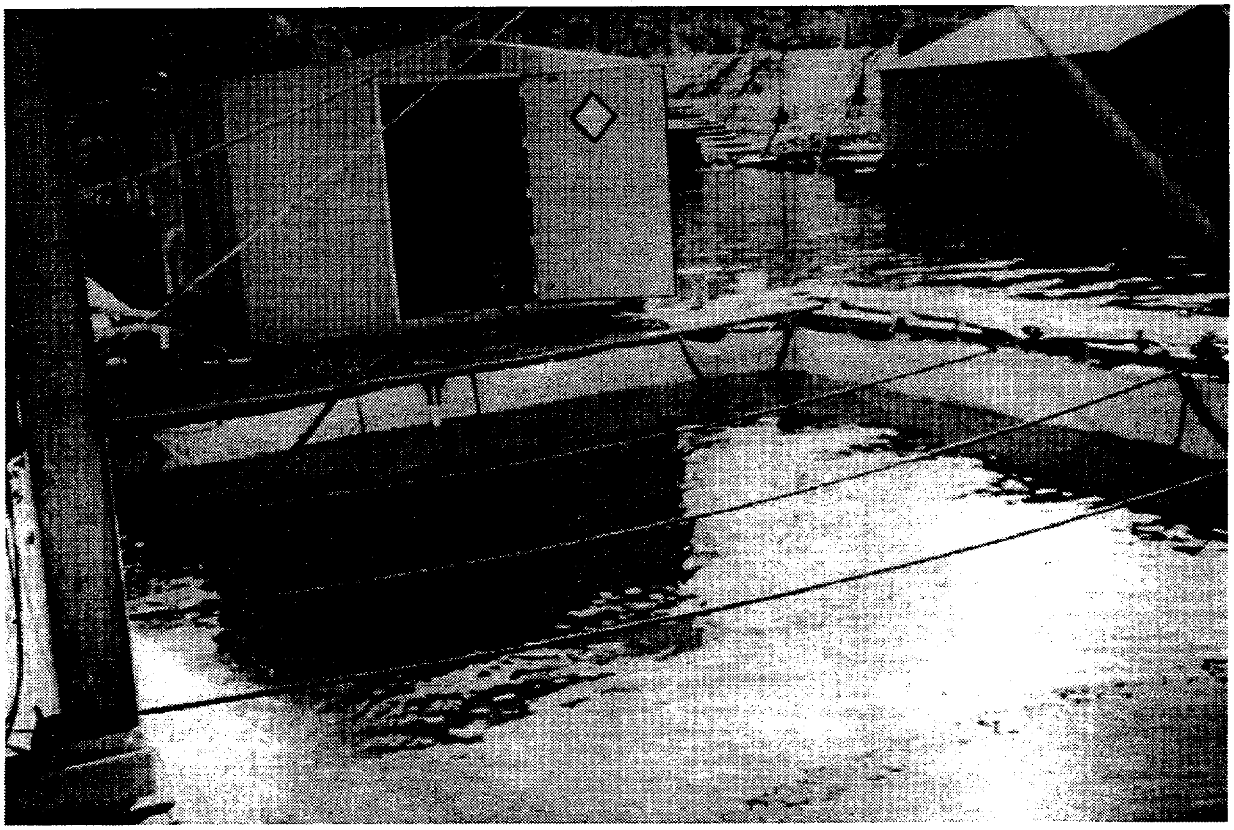


Figure 13

MR. PLOSKEY: I'm going to take you away from the net pens and out into the tailrace at Richard B. Russell (RBR) Dam. The graph on the left shows a plan view of the tailrace and standard transects that we sampled with boat-mounted mobile hydroacoustics, and the map on the right shows the location of RBR Dam on the Savannah River (Figure 1). I'm going to describe two sets of experiments that were conducted here. One set involved the use of a single ultrasound transducer to repel blueback herring in standing water, and the other set evaluated the effectiveness of a prototype sound system in flowing water during pumpback tests. In single transducer experiments, we tried to redistribute blueback herring with 130 -kHz sound, and we monitored distributions of blueback herring with mobile and fixed-aspect hydroacoustic gear. Some of the initial work involved mobile sampling of transects under sound-on and sound-off treatments.

What you see here are two echograms (Figure 2). The upper one represents a sound-off treatment, and the bottom echogram represents a sound-on treatment. If you're not familiar with echograms, this is a lot like reading ink spots. You have a surface echo appearing as a line at the top, and you have a thick, solid echo from the bottom. The white spots between the surface and bottom represent echoes from schools of fish. Transect 1 was sampled with a boat moving from left to right at -1 m/s parallel to and 5 m downstream from the face of the powerhouse. The upper echogram shows fish distributions during a sound-off treatment. As soon as the boat finished sampling the sound-off treatment, a high-frequency sound transducer mounted on the face of the dam and aimed downstream was turned on. The transducer was located near the top of the vertical white line shown in each echogram and was aimed out of the figure toward you. After 5 min, Transect **1** was sampled again, and we recorded the distribution of fish shown in the bottom echogram of Figure 2. These types of tests were repeated for several months, always on weekends and in slack water. There was no pumpback at that time because the pump schedule was delayed, which was a common occurrence.

This slide (Figure 3) shows Transect 2 located 25 m downstream from the face of the dam under sound-off and sound-on treatments . The redistribution of blueback herring is pretty impressive. Next we sampled Transect 3 located 50 m downstream from the face of the dam under sound-off and -on treatments (Figure 4), and some redistribution is still evident. Let me back up a second. One of the features of RBR Tailrace is that it's deeper right at the face of the dam and gets shallower as you move downstream. The slope of bottom is -5 to 1, so straight downstream is not a good direction to aim a transducer unless it is mounted near the water's surface and aimed horizontally or mounted deeper and aimed upward over the 5 to 1 slope. Sound transmitted from a deep transducer aimed horizontally downstream likely would echo off the rock slope and return toward the dam. Most of our preliminary testing was done with a single transducer mounted near the water's surface and aimed downstream.

Now, this is a new orientation (Figure 5). We're looking down on the tailrace in a plan view. We had a 420-kHz monitoring transducer and a 130 -kHz repelling transducer for redistributing herring mounted on the dam, 1.5 m below the water surface, and aimed downstream. In this plan view, the face of the dam would be at the top of the echogram and both transducers would be aimed down the graph from the top. Time is displayed along the x axis, and range from the dam is displayed along the y axis. So we are looking at horizontal distributions of blueback herring within -6 m of the water surface through time. Diagonal streaks from -40 to 100 ft during sound-on treatments are evidence of schools of blueback herring moving away from the sound source (Figure 5). When the repelling transducer was turned off, streaking stopped.

Here are two more echograms with the same orientation (Figure 6). In the upper echogram, we have a sound-off treatment followed by a sound-on treatment in which we see a little streaking and a general clearing of the targets. Again in the lower echogram, we see a similar response to a sound-on treatment. Here is another example (Figure 7). Sound was turned on shortly after we began recording this echogram. You can see high densities of fish within the first 100 ft of the tailrace, but through time densities decreased and there was some evidence of streaking from short to long range. Of course not all fish responded because not all fish present were blueback herring.

During one survey of transects l-5 with the hydroacoustic boat, we deployed a high-frequency hydrophone and measured the drop in sound intensity of 130-kHz signals from the source level that we were transmitting, which was -189 dB. When we plotted relative density of fish as a function of dB down from the 189-dB source level (Figure 8), we found consistently low densities at sound pressure levels above -145 dB. At sound pressure levels <145 dB, densities were high or low, depending on how many blueback herring *were* present when we sampled.

We also found that we could attract blueback herring to underwater lights. Both the upper and lower echograms on this slide have the monitoring transducer at the top just below the water's surface, aimed down, so you see a surface echo and a bottom echo (Figure 9). Time is on the x axis, and all echoes between the surface and the bottom are fish. We are looking at fish recruitment around this underwater light, obviously a powerful attracting stimulus. Next, we tested effects of interacting stimuli, with light as a continuous attractant and sound as an intermittent repellent (Figure 10). In both the upper and lower echograms, we see blueback herring recruiting around an underwater light. When we turned the sound on, schools were completely dispersed for -30 sec, maybe as much as 60 sec. But fish returned to the light in spite of sound transmissions.

So what was going on? In those sound/light experiments, which went on for about a month, relative effectiveness seemed to depend on what stimulus was applied first. If we applied the light first, we could disperse blueback herring schools only temporarily with ultrasound. However, if we applied sound first, we could keep blueback herring schools from recruiting to the light. They would swim through the illuminated zone but would not stay. These observations were very interesting, although by no means definitive, and by no means quantitative.

Here are some conclusions. Successful repulsion sounds ranged from 120 to 130 kHz and generally had amplitudes >145 dB//1 μPa@1 m. We were relatively effective in redistributing blueback herring at 82 ft and moderately effective at 165 ft. Effectiveness was related to sound intensity and therefore to the angle off the primary axis of the acoustic beam. Blueback herring were attracted to light. They could be repelled, but only for a short period of time. It looked like sound was an effective repellent but not a panacea because some fish appeared to acclimate to a constant frequency after about 45 min. In fact, some of them seem to layer out in the thermocline to avoid sound. We began to think about problems of continuous exposure and considered leaving refuge areas with minimal high-frequency sound and changing frequencies to reduce acclimation. We looked at continuous vs. pulsed sounds and found no obvious differences in echograms.

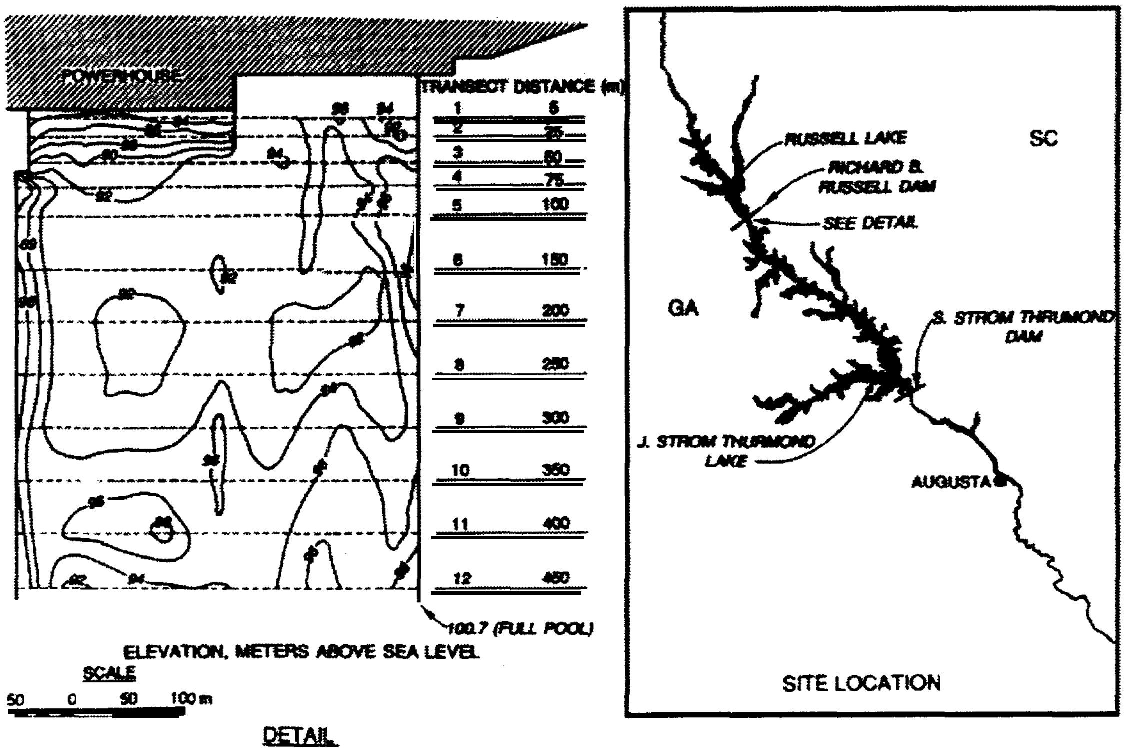
We developed a concept for deploying a prototype system at Richard B. Russell Dam that took advantage of flow patterns, high-frequency sound, and attracting lights (Figure 11). To deter blueback herring from staying in entraining flows, we created an acoustic field of ultrasound in front of pump turbines, hoping it would be effective out to -165 ft. We deployed high-pressure sodium lights around the edges of the channel near eddies to attract fish. Not that lights would attract fish from great distances, but we knew from light tests that if fish wandered into the zone of illumination, they would stay there.

We did a number of two-unit pumpback tests at -14,000 cfs with a full fish-protection system in operation. We compared numbers and lengths of entrained blueback herring under several test treatments, including day vs. night, sound-on vs. sound-off, strobe lights-on vs. strobe lights-off, and before and after installation of a 2-inch bar rack. We found that day pumping was a disaster even with the fish-protection system. Day pumps entrained thousands of blueback herring in minutes and taught us (as quickly as touching a hot stove) that day pumping must be avoided. We later discovered that blueback herring, which are surface-oriented at night, formed dense schools and layer out near the bottom at the base of the dam during the day. Clearly, diel behavior of fish is an important consideration for fish protection, not just fish responses to light or sound.

I am going to focus on sound-on vs. sound-off tests which were conducted at night without strobe lights and after the 2-inch bar rack was installed. For the evaluation, we had a net upstream to catch entrained fish. This was a big, 180-ft long, 80-ft deep, and 40-ft wide net attached to slides on either side of the penstock opening and required lots of people to deploy, fish, and remove (Figure 12). The net was lowered and dragged out to its sampling position with boats (Figure 13). At the end of the net, we used a frame of wedge wire between the pontoons of a boat to separate fish from entraining flows so they could be processed by the Fish & Wildlife Co-op Unit of the University of Georgia (Figure 14) . Here is what the 8-ft wide pontoon barge looked like when it was deployed at the start of pumpback (Figure 15). You are looking at the surge of -6400 cfs, which was impressive. We were afraid to have people on the barge during startup.

In setting up a design to evaluate sound-system effectiveness, we focused on night hours in which entrainment was above some threshold, reasoning that fish must be present before they can be deterred. We selected two 15-min 'on' treatments at random within each hour. Sometimes there were two consecutive sound-off or sound-on treatments. Here are results of four nights of testing, which was all we were allotted by the resource agencies and by the Savannah District (Figure 16). Generally, you see that blueback herring entrainment was lower during sound-on treatments than during sound-off treatments. A two-tailed t-test, assuming unequal variances, was significant at a 5% level. It indicated that average entrainment rates were 56% lower when high-frequency sound was transmitted than when it was off (Figure 17) . This slide shows entrainment of all fish (upper panel) and of blucback herring (lower panel) during Phase I and Phase II pumpback testing (Figure 18). Phase I was basically one-unit pumpback with an unconfigured sound system. Transducer orientations were modified between Phase I and Phase II to increase acoustic coverage, at the suggestion of John Menezes. In Phase I, all transducers were aimed straight downstream, and deep transducers were aimed upward from the horizontal at -20° to avoid the bottom. For Phase II, transducers on either side of every pump intake were aimed 45° off the face of the powerhouse so they crossed in front of the pump intakes. Phase II testing of two-unit pumpback went quite well, and blueback herring entrainment was not the concern it was before Phase II. There were other factors reducing entrainment, including the bar rack, but we were confident that at least half of the observed decrease was due to high-frequency sound.

Russell Dam and Tailrace



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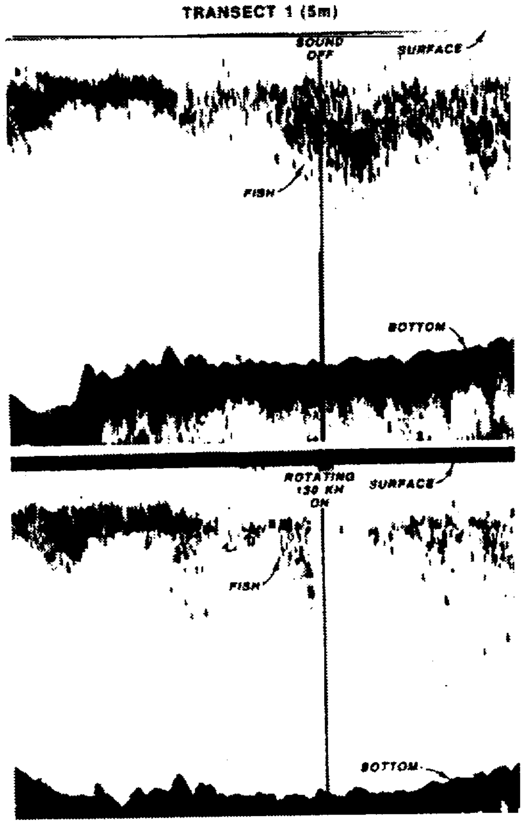


Figure 2

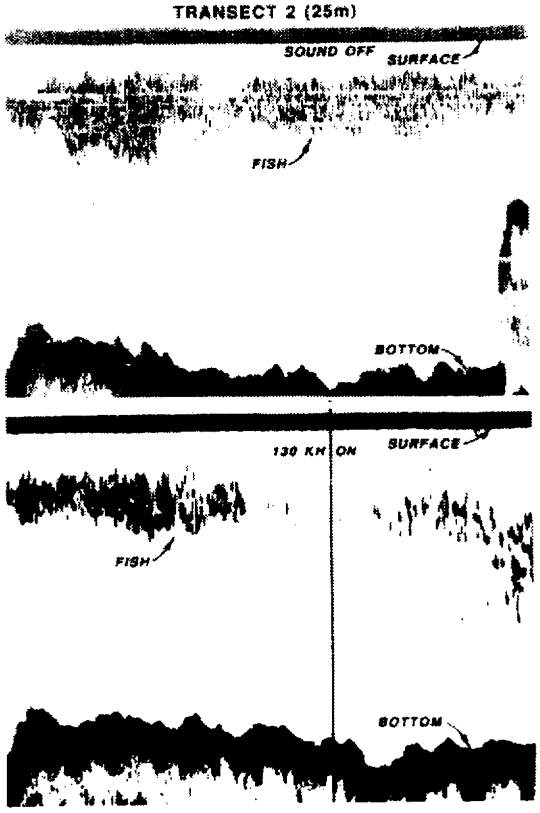
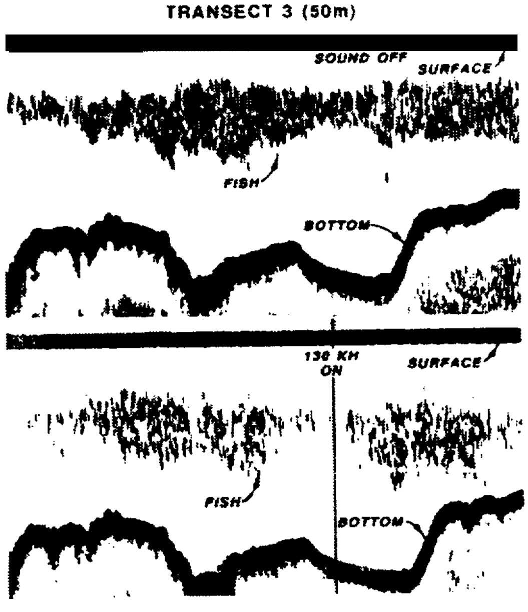


Figure 3



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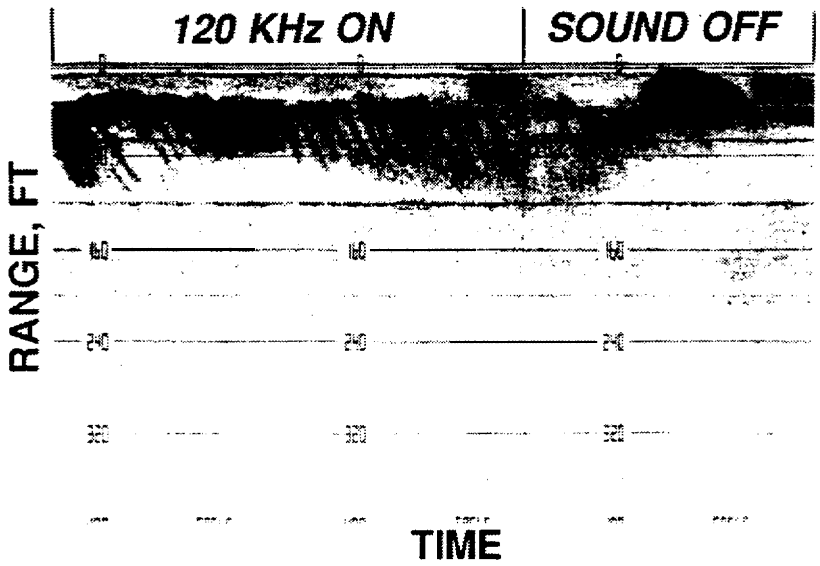
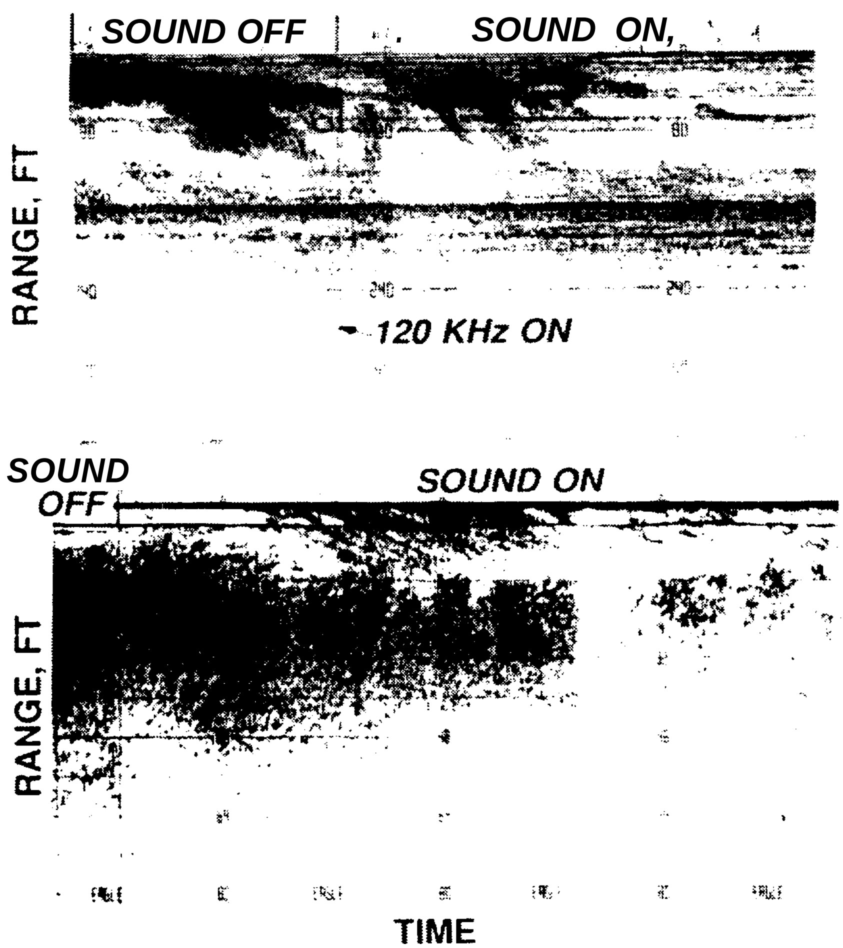


Figure 5



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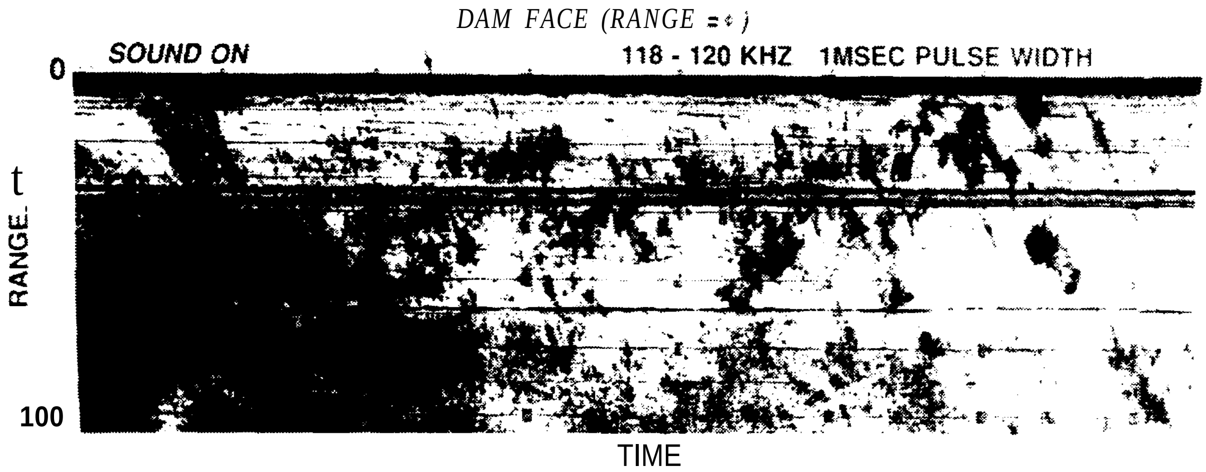

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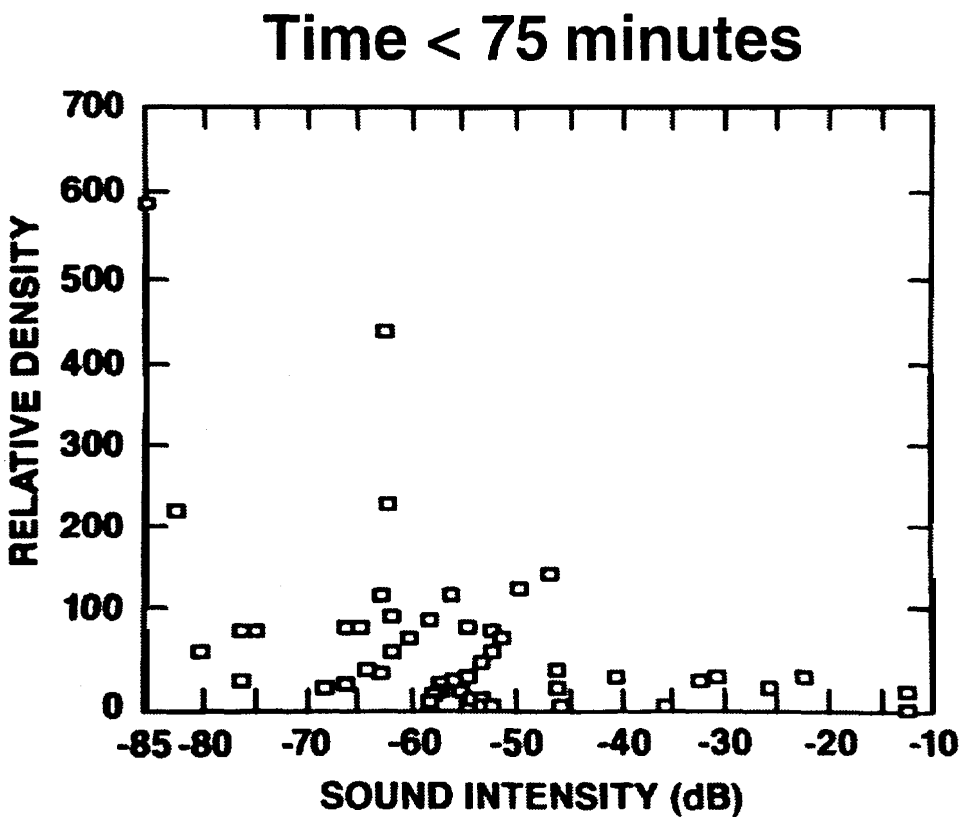
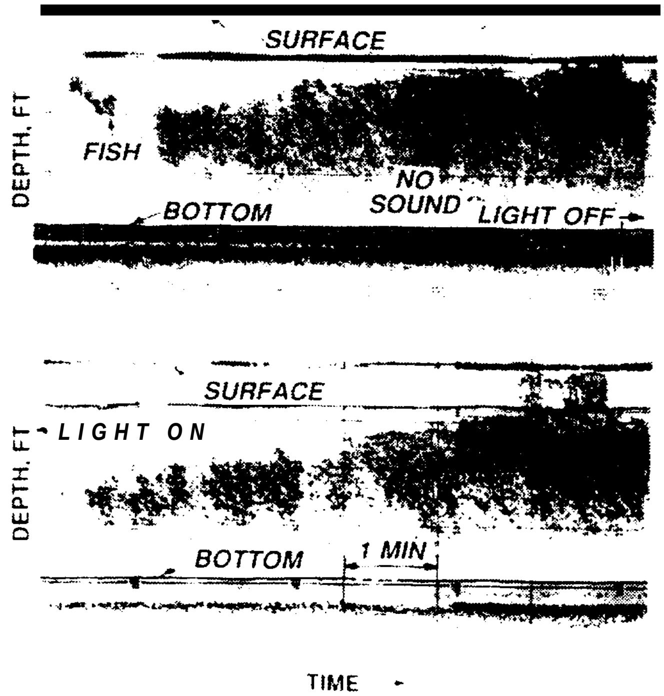


Figure 8

UNDERWATER LIGHTS



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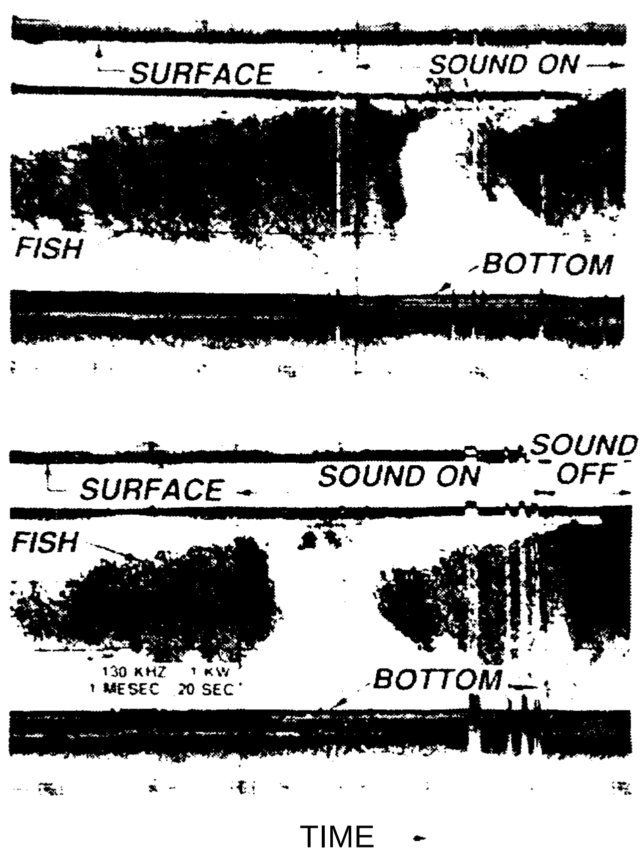


Figure 10

Concept-Deployment of Behavioral Technology

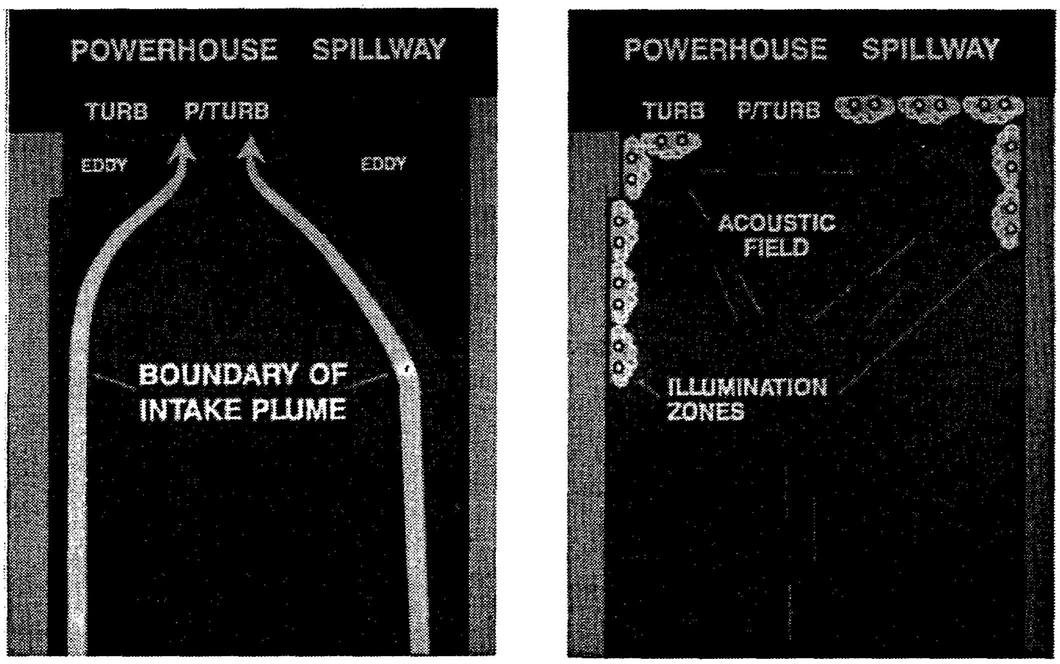


Figure 11

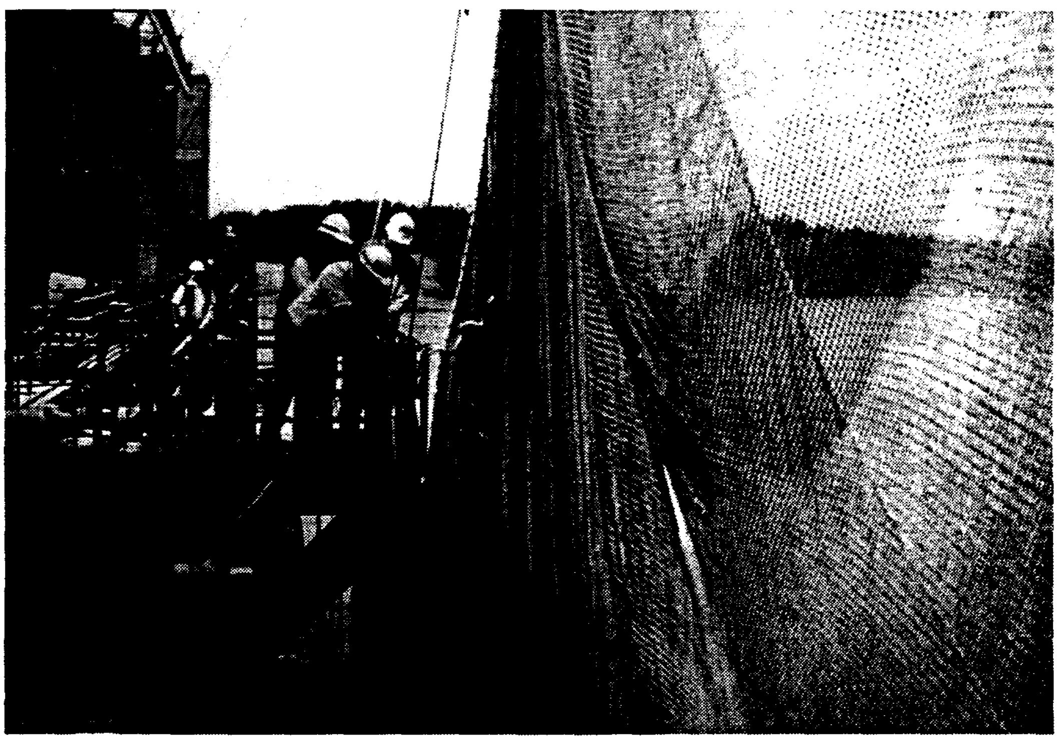


Figure 12

Figure 13

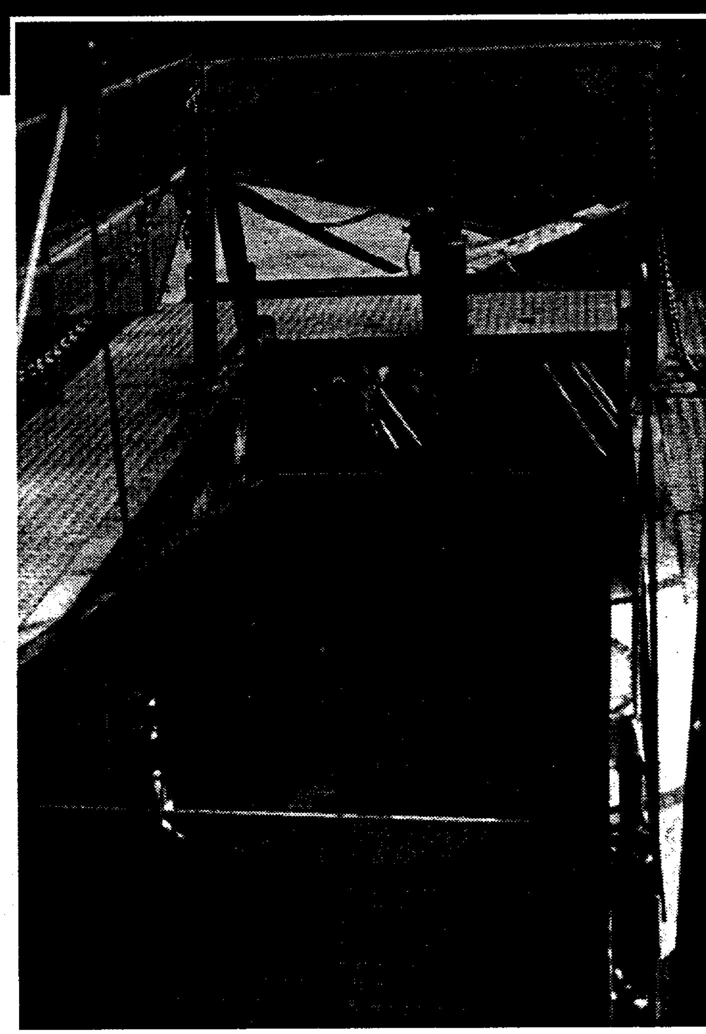


Figure 14

Figure 15

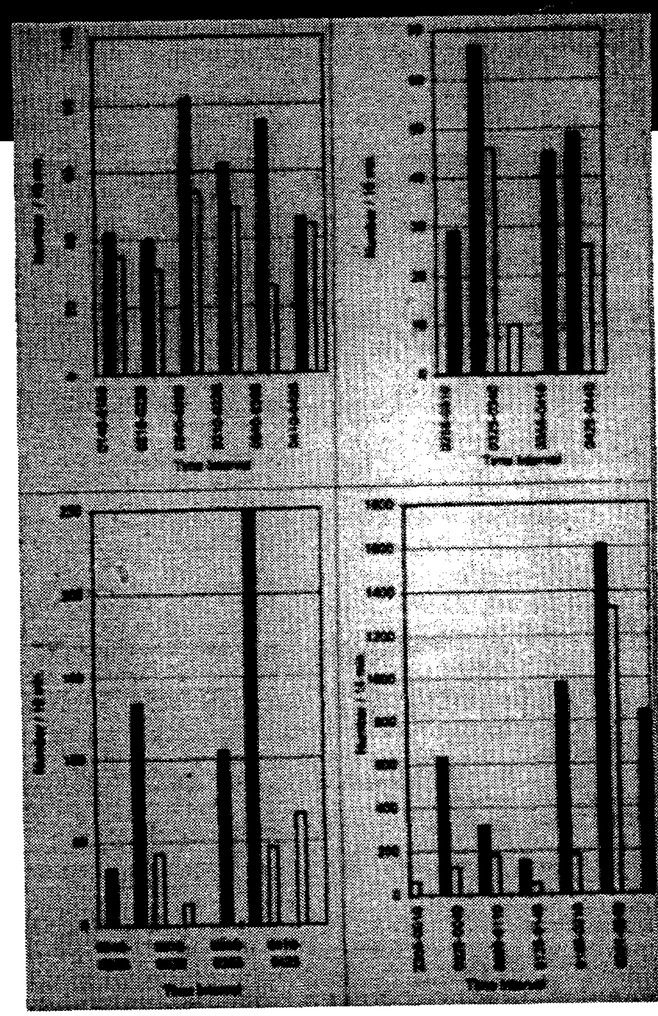


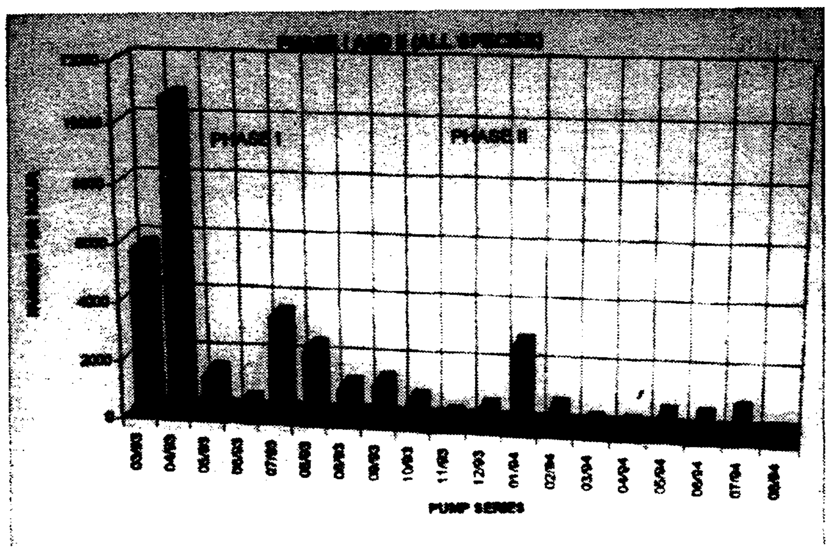
Figure 16

Effect of high-frequency sound on blueback herring passage through turbines at Richard B. Russell Dam

Two sample t-test assuming variances among sound treatments

Statistics	*Sound On Variable 1*	*Sound Off Variable 2*	*Sound On Unloggged mean*	*Sound Off Unlogged mean*
Mean	1.65	2.01	44.67	102.33
Variance	0.22	0.28		
Observations	24	24		
Pooled variance	3.5			
t	- 2.49			
P (T ≤ t) one-tail	0.01			
t Critical one-tail	1.68			
P (T ≤ t) two-tail	0.02			
t Critical two tail	2.01			

Figure 17



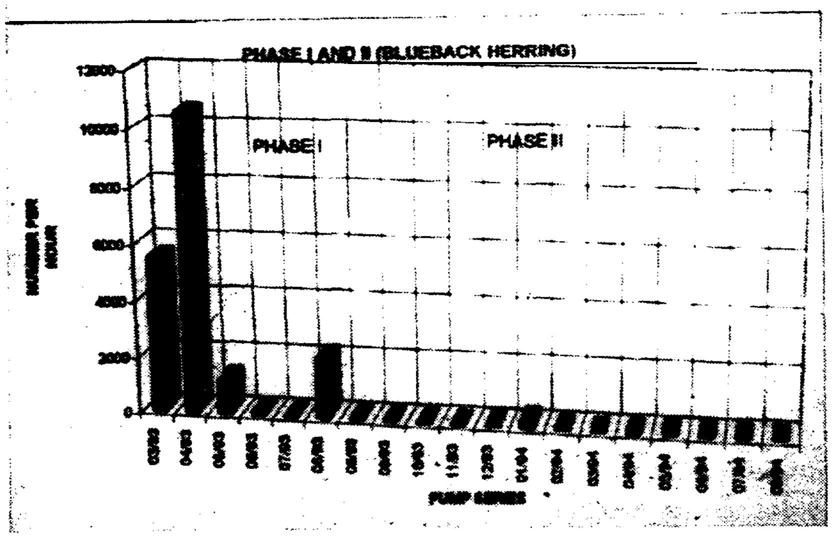


Figure 18

Entrainment rates of all fish and blueback herring during Phase I and Phase II pump-back testing at Richard B. Russell Dam

Infrasound/Electric-Field Fish Fence: Atlantic Salmon

Michael Clegg
Simrad Aberdeen Ltd.

Simrad is an international company with headquarters in Norway. Its core business is based either under the water, on the water, or in the water. This includes process control for the offshore oil and gas industry, ocean topography for ocean sciences, mine detection and anti-submarine equipment for Naval defense, echo sounders and fish finders for the fisheries industry, and positioning systems for ocean-going yachts. Simrad has manufacturing and distribution in the US., Canada, Norway, and the U.K., and has been in business since 1947.

Simrad annually invests 10% of its gross revenues in research & development with a philosophy of finding solutions that clients either want now or will soon ask for. As a commercial company based in Scandinavia where environmental issues are faced head-on, it is not surprising that Simrad has invested heavily over the last seven years in this developing technology.

Originally the fish-fence project grew out of the idea of investigating possibilities for developing large-scale aquaculture, making use of the many deepwater fjords that make up much of the Norwegian coastline. The intention was to contain large numbers of cod in the fjord by way of a non-physical barrier at the narrow mouth of the fjord inlet. By this method, it was envisioned that the fish would have sufficient space so as not to be stressed, that the water space would be cleaned naturally, and that there would be no inherent problems of net management. Following preliminary trials in 1988 using Atlantic cod, it was established that it was possible to contain the fish using acoustics, although they would habituate after a period of time and cross the barrier for food. However, when the acoustics were reinforced with an electric pulse, the fish turned back.

From these trials, the philosophy of the two negative stimuli evolved, acoustic and electric, especially when dealing with resident fish populations.

Acoustic The acoustic transducer device consists of an electromagnetic linear motor driving a rubber diaphragm (Figure 1). The unit contains its own power amplifier and electronics, as well as a device to monitor return, and is depth-compensated to alleviate any problems with impedance miss-matching. The unit can be driven in frequencies ranging from 2 to 32 Hz, with either a sine-wave or square-wave input. Present construction allows the units to operate down to an equivalent depth of 2 barometers or 65 ft.

The system consists of an array of transducer units, in this case up to 20, that can be configured to operate as a monopole or dipole (Figure 2). The frequency range can be adjusted to vary between 2 and 32 Hz, with either a sine-wave or square-wave output. The output level can also be adjusted from -12 dB to 0 dB, where 0 dB represents 120 W RMS (root-mean-square). A modified square wave was adopted after tests at the Sintef facility in Trondheim, Norway showed that it would maximize acceleration for the size of transducer, compared to a sine-wave function.

Electric The electric system (Figure 3) comprises a number of stainless-steel electrodes suspended either horizontally or vertically in the water (depending on site conditions, i.e., conductivity, depth, topography, etc.). These are connected to power units capable of producing up to 1800 vDC, pulsing at the same frequency as the acoustic transducers and delivering a pulse duration of 0.5 ms. The energy in each pulse can be varied by selecting different combinations of capacitors, from 56 to1261 μF (micro-farads). The wave form can be either sine or square wave. The square wave gives a sharp leading edge and maintains the voltage at its peak for the longer time. The triggering of the system can come from synchronization with the acoustics or from its own internal clock.

Installing the electric fence in the same plane as the acoustic transducers ensures that the fish that do habituate across the acoustic field feel some pain and associate it with the sound source. The fish are able to detect from where the acoustic source emanates but are unable to locate the origin of the electric field.

Two systems that I'll describe to you were develped and tested from these early trials. It's not my intention to make any claims for these systems, only to describe the installations and explain and detail our observations. The two systems installed and tested to date are at (1) the Dunkirk Steam Station on Lake Erie, New York, for Niagara Mohawk Power Corporation in the autumn of 1992, and (2) the Echnaloch Bay in Scotland, as part of the EU AIR Programme in the spring of 1994.

Dunkirk The Dunkirk steam station is located in western New York State on the eastern basin of Lake Erie (Figure 4). The station has a total generating capacity of 628 MW from four coal-fired boilers that collectively utilize 1514 m^3/min (400,000 gallons/min) of cooling water. Water for the once-through condenser cooling system is drawn from the lake via a shoreline intake. The water passes under two skimmer walls, northern and southern, designed to exclude large floating debris. The water velocity at this point under the skimmer walls, which are 183,5 m^2/min during full cooling-water pump operation, is 0.14 m/s (0.45 fps).

The test was carried out between 23 November and 14 December 1992, although installation started three weeks prior to this (Figures 5 & 6). For the purpose of the trial, the northern opening of the skimmer wall was blocked off with 9.5 mm (3/8 inch) mesh-size monofiliment net, to try to ensure that the fish could enter the forebav onlv via the southern opening where the barrier was installed. This blocking net was not altogether successful, because autumn leaves and other small debris built up against it and it tore in several places, despite reinforcement with steel mesh.

The trial supervisors for Niagara Mohawk devised a test program and provided the fish collection and sampling analysis (Figure 7). During the 'on' periods, the operating parameters of the fence (both acoustic and electric) were not changed at all. Each transducer in the 24-transducer array was delivering for the most part a 30-W output, working in a dipole configuration at a frequency of 8 Hz. The electric fence was producing1000 vDC, 4 ms pulses, with a compacitance of only 44 μF, giving an energy pulse of 31 joules. During operating times, the acoustic and electric fields were measured and recorded and 3-dimensional plots produced through slices in the fields (Figures 8-12).

The report showed that an estimated 6,079,272 fish were collected, of some 38 different species, some of which would have been hearing specialists of which 5,987,440 were actually impinged. Emerald shiner accounted for 5,964,388 fish, making up some 98.2% of the total. Of that total, 99.9% were <56 mm, or 2.2 inches long (Figure 13). And of the remaining fish, rainbow smelt was the second most abundant with a mean length of 68 mm, or 2.6 inches long. The third most abundant was yellow perch, with a mean length of 74 mm, or 2.9 inches long, and the fourth most abundant was gizzard shad, with a mean length of 82 mm, or 3.2 inches long. It was from these four species that the effectiveness was calculated. The effectiveness report to Niagara Mohawk, based on the four most-abundant species, suggested that the trial was inconclusive, at best. However, the number of fish >150 mm, or 5.9 inches long, were fewer than 50 out of approximately 6 million. During the tests, the electric field gradients and the acoustic field particle-acceleration peak amplitudes were measured and r ecorded.

Echnalock Bay, Scotland Before the tests at Dunkirk had started, we felt that to continue the development we would need more funding. An application was submitted to EU under the Air Programme. We teamed up with the Dansk Teknologisk Institut of Copenhagen, Heriot Watt University's group on Orkney, and VIFA, the loudspeaker manufacturer from Denmark. It was our intention to further investigate the real likelihood of using the barrier for large-scale fish farming.

The Orkney site (Figure 14) was chosen because it provided a sheltered location within Scapa Flow for the outsize sea cage and because the water is quite clear and acoustics are very good, providing close to free-field conditions.

The sea cage was moored half a kilometer from the beach in a water depth that varied with tide, between 9.5 and 10.5 m (Figure 15). Bottom conditions were fine, level sand with no pressure waves visible, no rocks, and very few clumps of kelp. Although the site was very well situated, it was still susceptible to northwesterly winds, giving a significant wave height of -0.5 m. The tidal current was measured as no greater than 0.5 knots, -0.25 m/s.

The sea cage measured 30m x 20m x 10m. The containment netting was 12 mm knotless untreated nylon, whereas the surrounding predator net (to keep out seals) was 120 mm. There were walkways and handrails all around the cage to enable the team to have access to all the areas. An anti-bird net was suspended over the top of the water to keep off the many predator birds. The walkways were hinged and articulated to reduce the stiffness and allow the structure to flex under wave action. These hinges meant that, under some sea conditions, the relative motion of the cage could be alarming; however, no test days were lost during bad weather.

A wooden pontoon was part of the structure above the test opening, which was fitted with additional buoyancy to support the fiberglass container with the operating and test equipment inside. It also gave some shelter for the personnel in bad weather. We approached the site daily by launch and small zodiac.

The test was divided into three sections, the two smaller areas separated with the same size containment net with similar openings of 2m x 10m. One opening had the fence array installed, whereas the other opening was an escape option. Both openings could be closed off by dropping a weighted containment net over them. The equipment was installed with the help of divers and suspended from a beam running under the pontoon.

Power for the system and monitoring equipment was supplied from a 53-KVA ‘hush power’ generator on the beach through a subsea cable towed out by the launch. By siting the generator on the beach, the cage was isolated from any vibration effect. Monitoring was provided by two underwater video cameras and a Simrad EY 500 echo-sounder with a split-beam transducer ranged at the space behind the barrier.

The cage was populated in the first instance with 200 ‘two-winter’ salmon of average size, 5-7 kg (fish that have spent two winters in seawater), and 200 ‘one-winter’ salmon of average size, 2-4 kg (fish that have spent one winter in seawater). The fish were supplied by a local fish farmer. The fish were allowed to acclimatize for 5 days and given free access to all parts of the sea cage. Because they were farmed fish, they had to be fed; but the feeding was reduced, and they were fed irregularly and at all parts of the enclosure. They were very active and soon enjoyed the freedom of the large area.

After 5 days, the fish were herded into the large area and the two openings closed off. There then proceeded two control tests without any equipment running, to ensure that the fish had no preconceived preference for one or the other opening. Once the fish were in the large area, the two openings were reopened and the fish were slowly driven using a sweep net. Once the drive was complete, the nets were dropped and the fish counted. The result showed that they had no preference for one over the other. Despite the physical presence of the transducer and electrode array, the ratio came out at 50/50 give or take 1–2%. On completion of the count, the nets were lifted, the fish were fed and allowed to rest for 24 hours, and were once again given the complete run of the cage.

The tests then continued along the same lines with only the acoustic system running and with the output set at half-power with the fish being driven. Upon activation of the acoustics, the fish were seen to immediately evacuate the area in front of the barrier and move to the far end of the large area. The number of fish actually passing through were less than 5 in number (all ‘two winter’ fish).

We then changed the test by containing them in the large area and withholding food for 2 days, then enticing them across by feeding in both areas. Initially all of the fish preferred the ‘safe’ area; but by leaving the system running for a prolonged time period, more of the larger ‘two winter’ fish disregarded the barrier until a hard core of 35-40 fish would traverse the barrier for food seemingly unperturbed.

After resting the fish again, the drive tests were restarted with the electric field operational at 200-V potential alongside the acoustics. The immediate response of the rish on activation of the acoustics was to once again dash to the far end of the large area. On completion of the drive, the results were the same as if only the acoustics were on, with only 5 or so fish crossing over. Again, none of the fish were ‘one winter’ fish.

The tests were repeated, slowly raising the potential up to 600 V, and at this time no fish passed through. After repeating the test at 600-V potential, at least 3 fish would cross over. Whether they were the same fish, I don’t know. However, it could be seen on the video that they were in considerable discomfort, with severe body twitching and a rolling motion.

The food enticement tests were also carried out with the 600-V potential, and numerous fish were seen congregating at the vicinity of the fence, approached as if to cross over, and then turned back. Some of those that turned back displayed signs of involuntary twitching as they got too close. When this test was repeated, one ‘two winter’ fish was seen to go through in great discomfort..

During the last few days of the food tests, we had 1200 new smolt delivered by helicopter to a holding net to acclimatize. During this time, we ‘lost’ -300 of them for no explainable reason.

Before beginning the tests on the smolt, the other 400 fish were removed. This was on the advice of our biologists and fish farmer, who considered that the smolt would be very stressed being in the same cage and that there was a likelihood of the larger fish eating them. Due to the size and number of the smolt, the test area was considerably reduced. However, as a general observation, the smolt were not feeding and their movement around the test area was sporadic and lethargic. At the initial turn-on of the acoustic system, an avoidance dispersion was noticed, although they quickly acclimatized and were seen swimming about the transducers apparently oblivious to the output. When the electric field was energized, as well as the acoustics, the fish showed no visible signs of discomfort, although they didn’t congregate around them as they did to the acoustic transducers.

We concluded that the system would be suitable for open-water sea farming, certainly as far as the ‘one winter’ and ‘two winter’ fish were concerned. It has also been shown by others that it is possible to condition the fish by feeding at certain times. As far as the reaction of the smolt is concerned, a number of scenarios have been put forward. The osmosis change from freshwater to seawater is very stressful, the reaction by wild and farmed fish in this stage of their life is very different, and the acoustic sound source was too small to have any lasting frightening effect. We understood before the trials that the electric field of that size would be very limited to fish of the smolt size in seawater due to the obvious problems with field dispersion in seawater with high conductivity.

The Future We have since increased the size of the transducer deflection and solved the problem that prevented the units from operating at full power for any length of time. We have been advised that a monopole configuration would be more effective than the previous dipoles, although I believe it is recognized that a dipole more closely mimics the fish reaction.

We are at present in the process of putting together a working relationship with the team from the University of Oslo, because our systems have a certain synergy since both of us are utilizing infrasound. We are putting forward another EU application to extend our knowledge of what is happening ‘acoustically’ in front of the dams, intakes, and bypasses that may affect the fish reaction and to help us when building new barriers. We are also going to extend our device to include eels which, in parts of Europe, are as important a cash crop as is salmon. We are also planning two more field installations during next year’s migration to get what is hoped to be the final sets of field data.

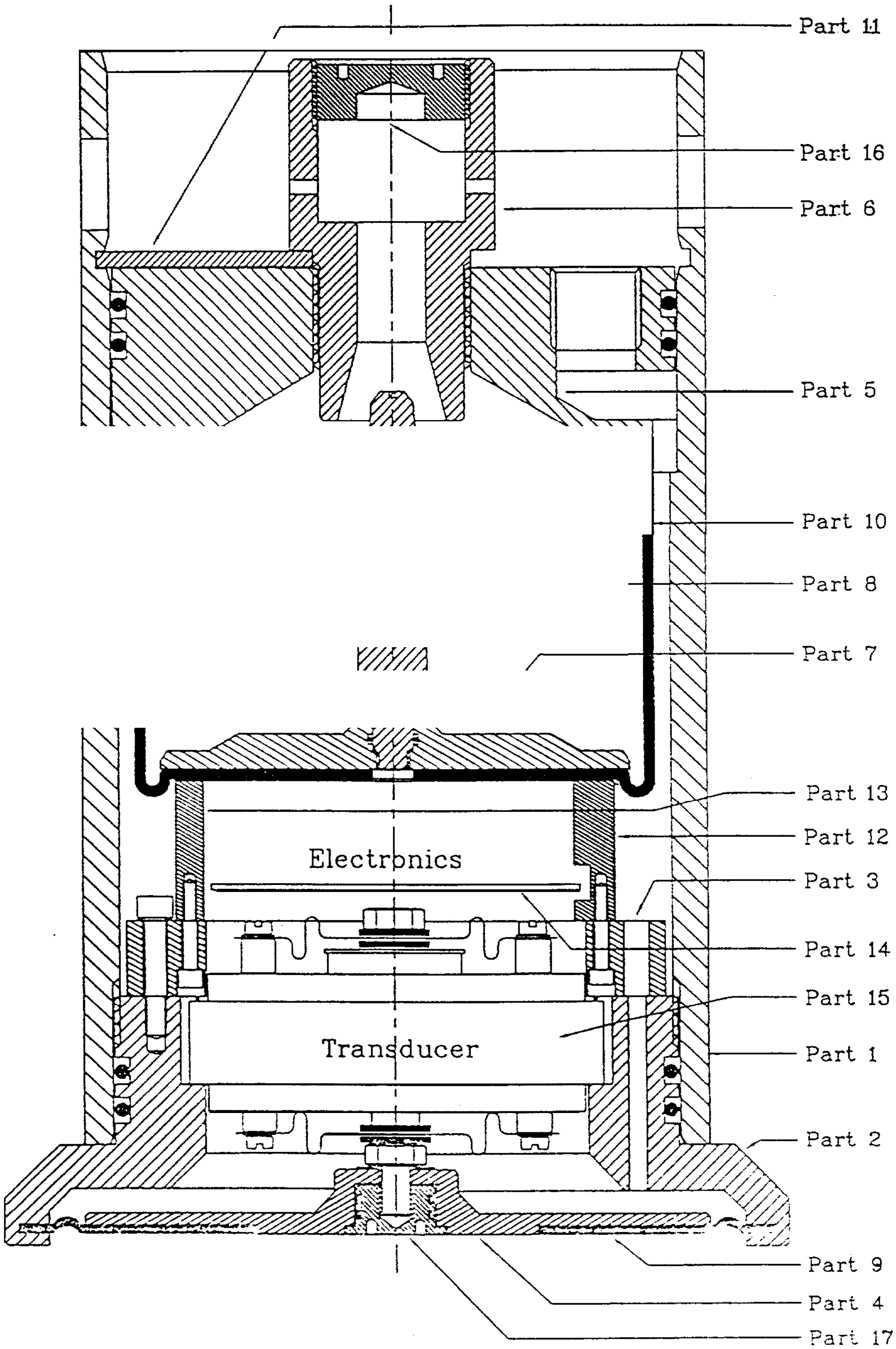
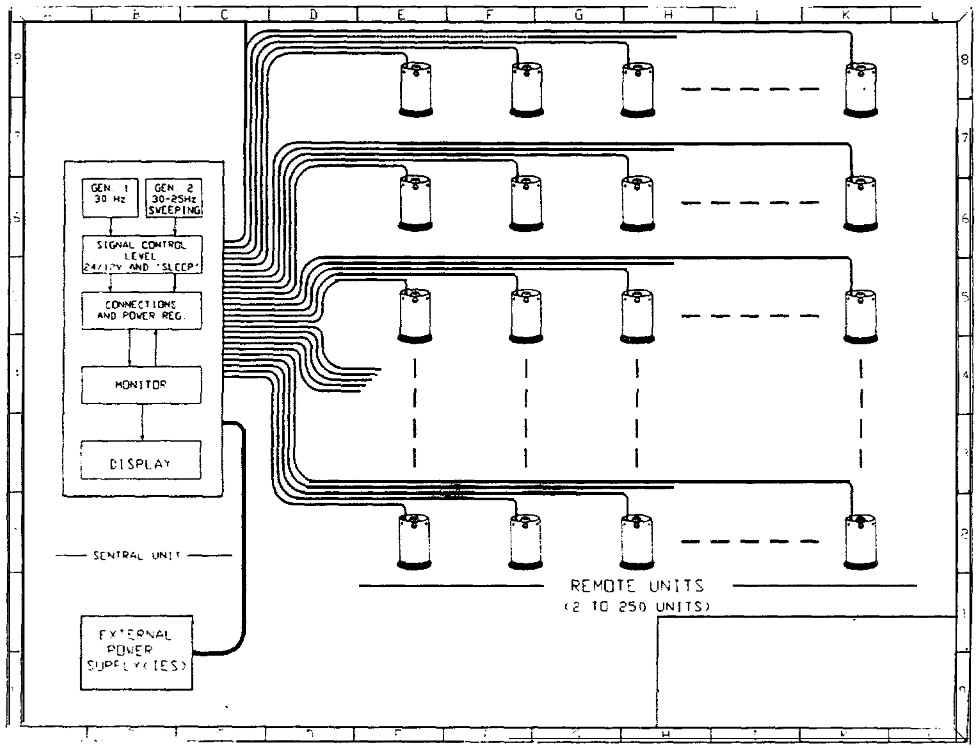

Part 11
Part 16
Part 6
Part 5
Part 10
Part 8
Part 7
Part 13
Part 12
Electronics
Part 3
Part 14
Part 15
Transducer
Part 1
Part 2
Part 9
Part 4
Part 17

Figure 1



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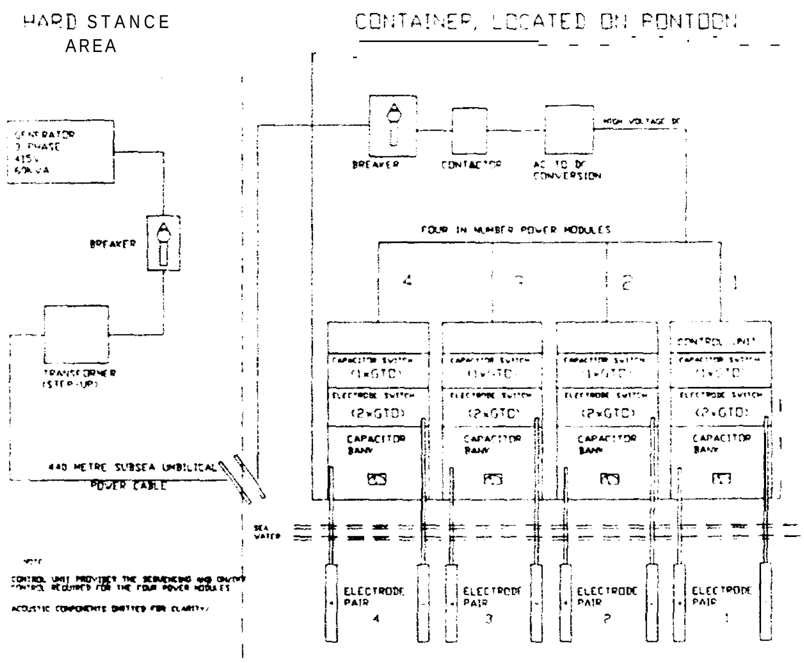

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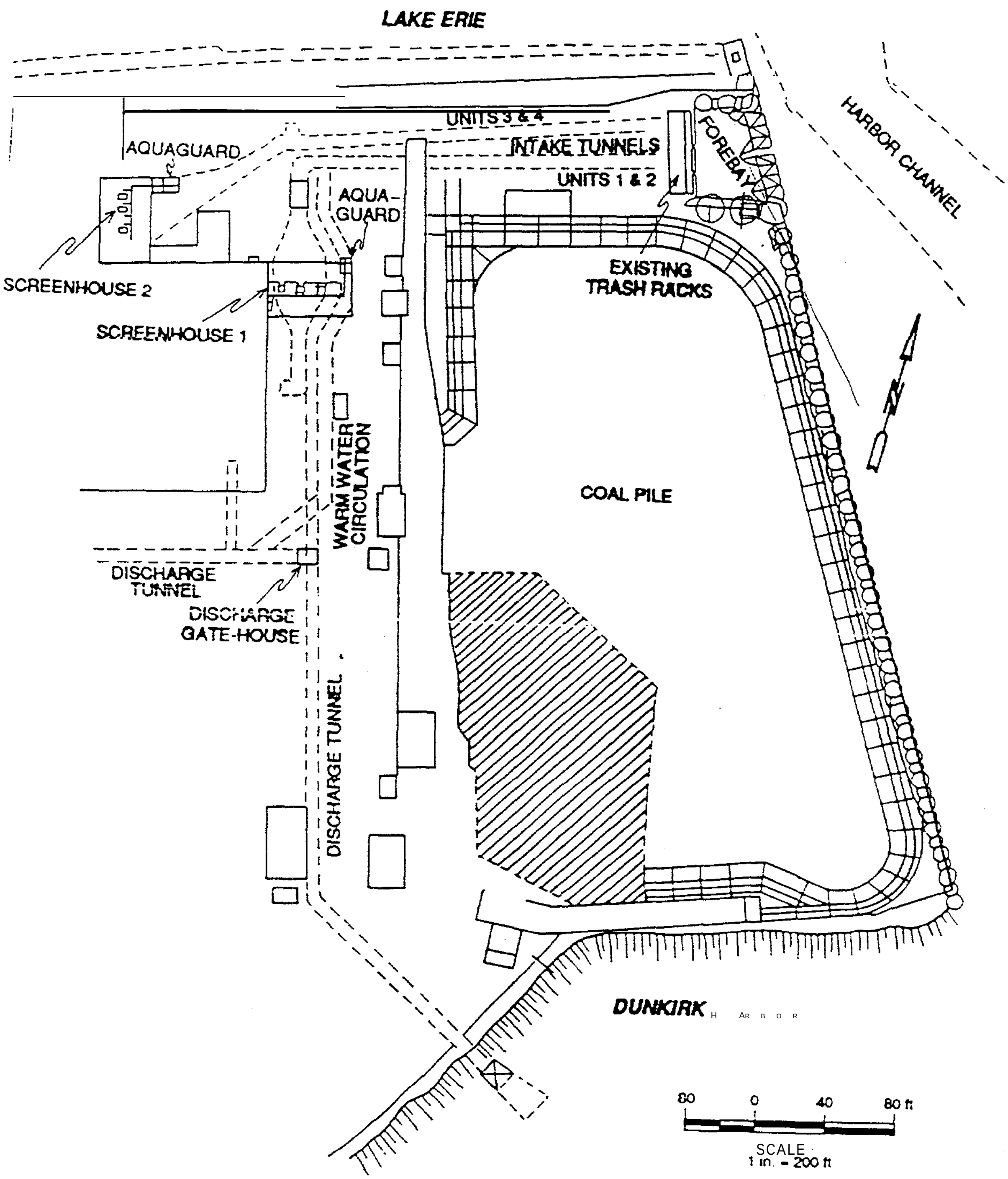
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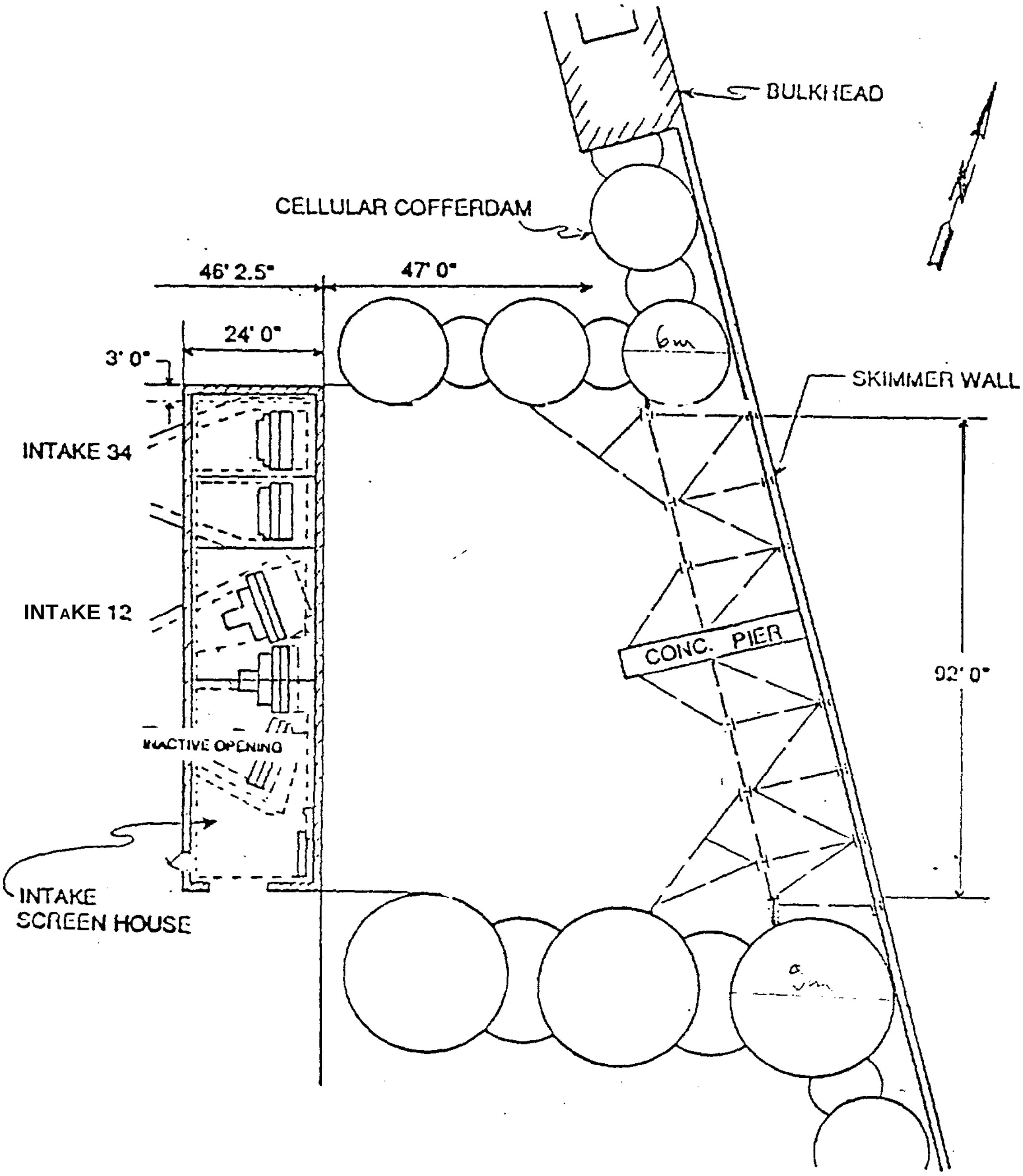
UNITS 3 & 4
INTAKE TUNNELS
UNITS 1 & 2
FOREBAY
HARBOR CHANNEL
AQUAGUARD
AQUA-
GUARD
SCREENHOUSE 2
SCREENHOUSE 1
EXISTING
TRASH RACKS
WARM WATER
CIRCULATION
COAL PILE
DISCHARGE
TUNNEL
DISCHARGE
GATE-HOUSE
DISCHARGE TUNNEL
N
DUNKIRK HARBOR
80
0
40
80 ft
SCALE
1 in. = 200 ft

Figure 4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CELLULAR COFFERDAM
46' 2.5"
47' 0"
24' 0"
3' 0"
6m
SKIMMER WALL
INTAKE 34
INTAKE 12
CONC. PIER
92' 0"
INACTIVE OPENING
INTAKE
SCREEN HOUSE

Figure 5

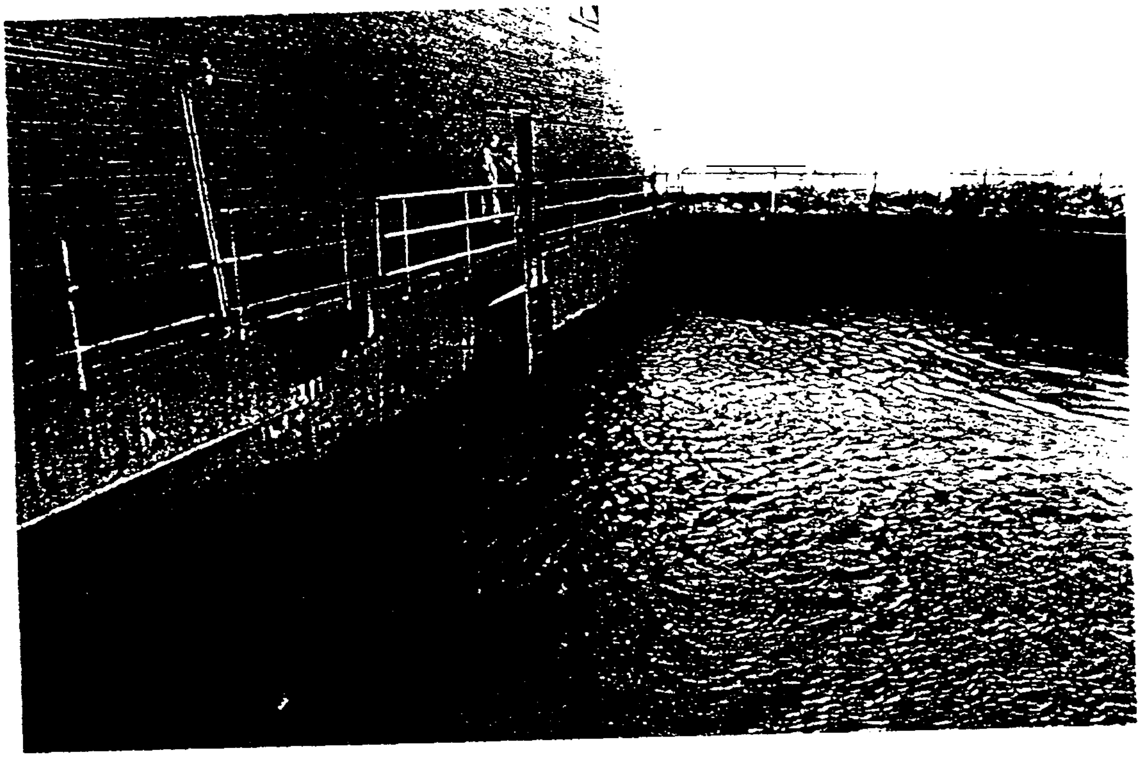


Figure 6

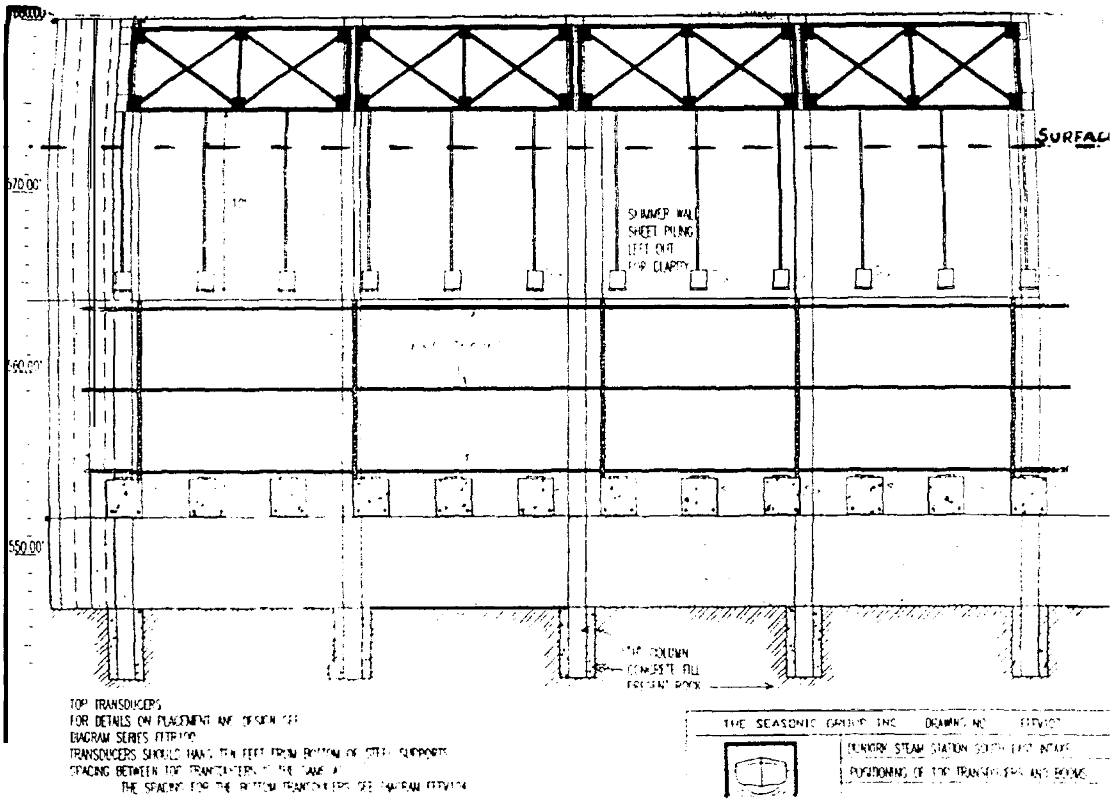
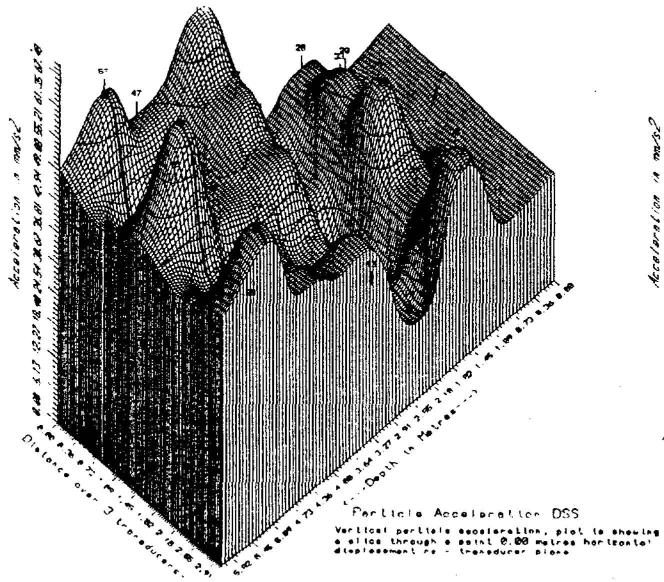
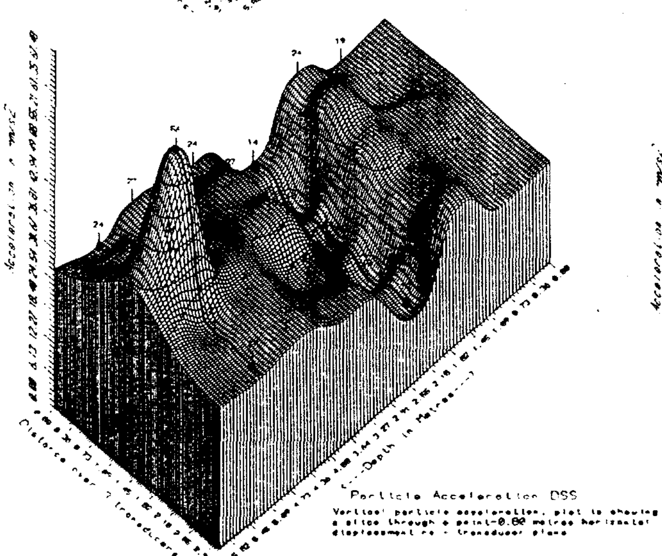
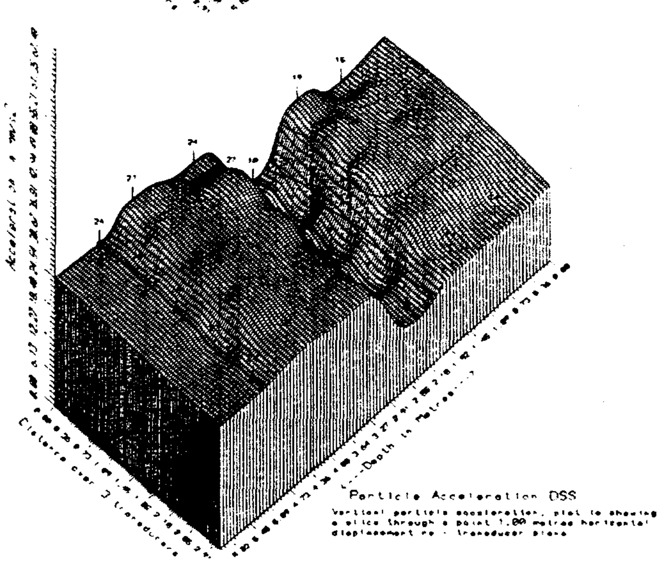


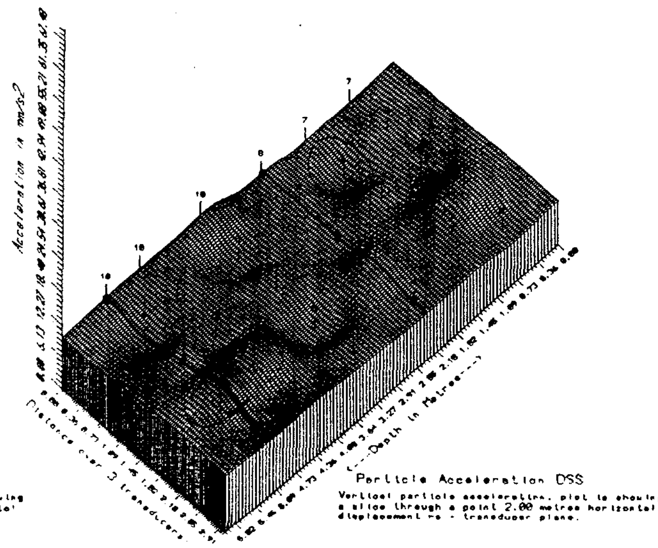
Figure 7

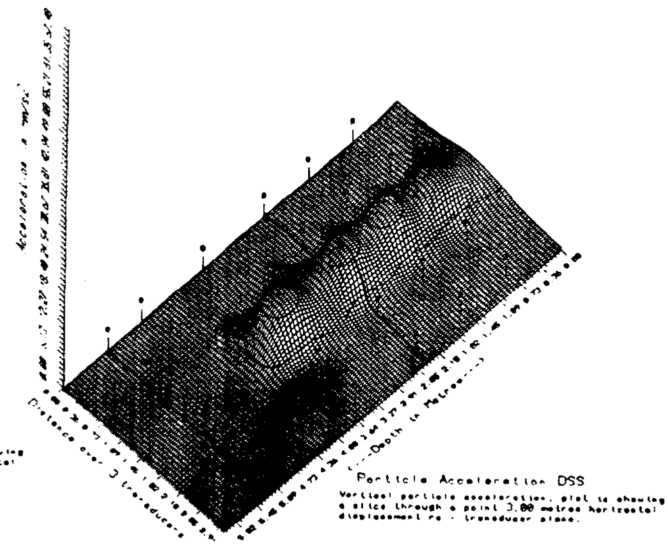






Figures 8-10 (top to bottom)





Figures 11-12 (top to bottom)

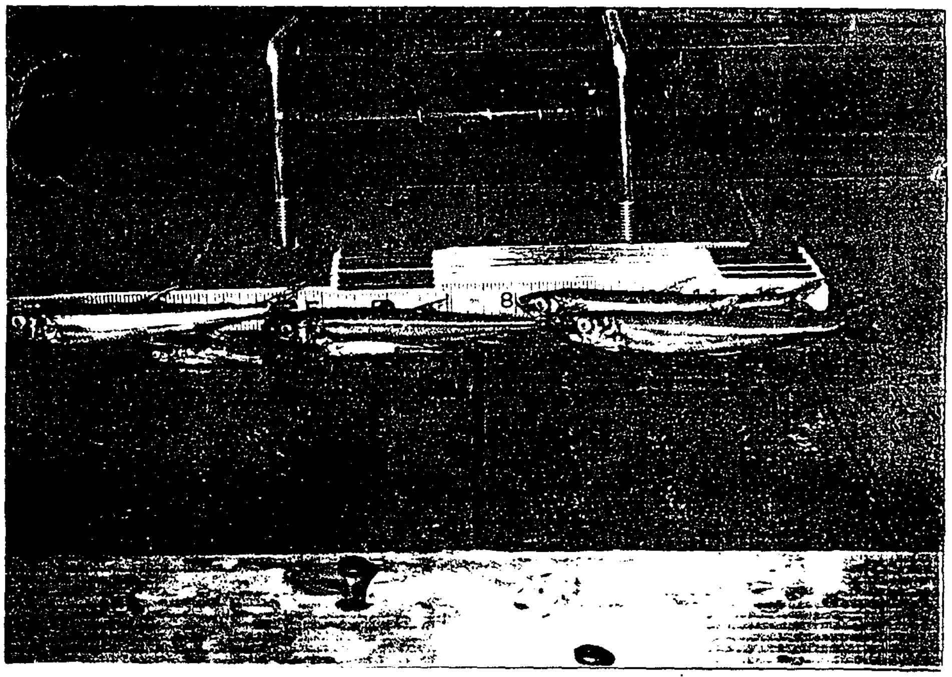


Figure 13

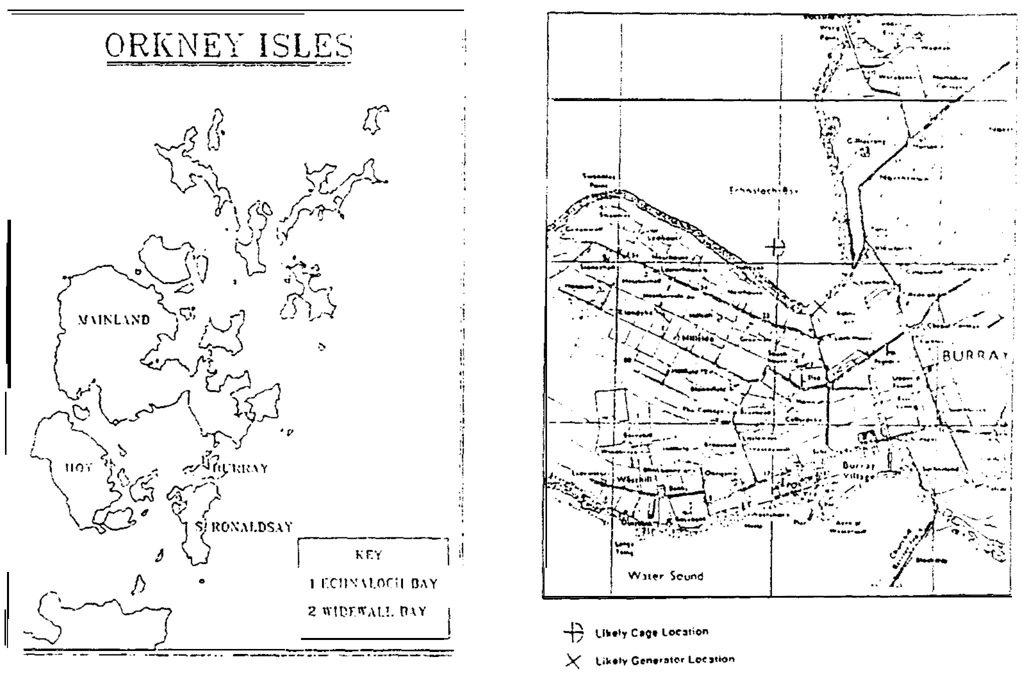
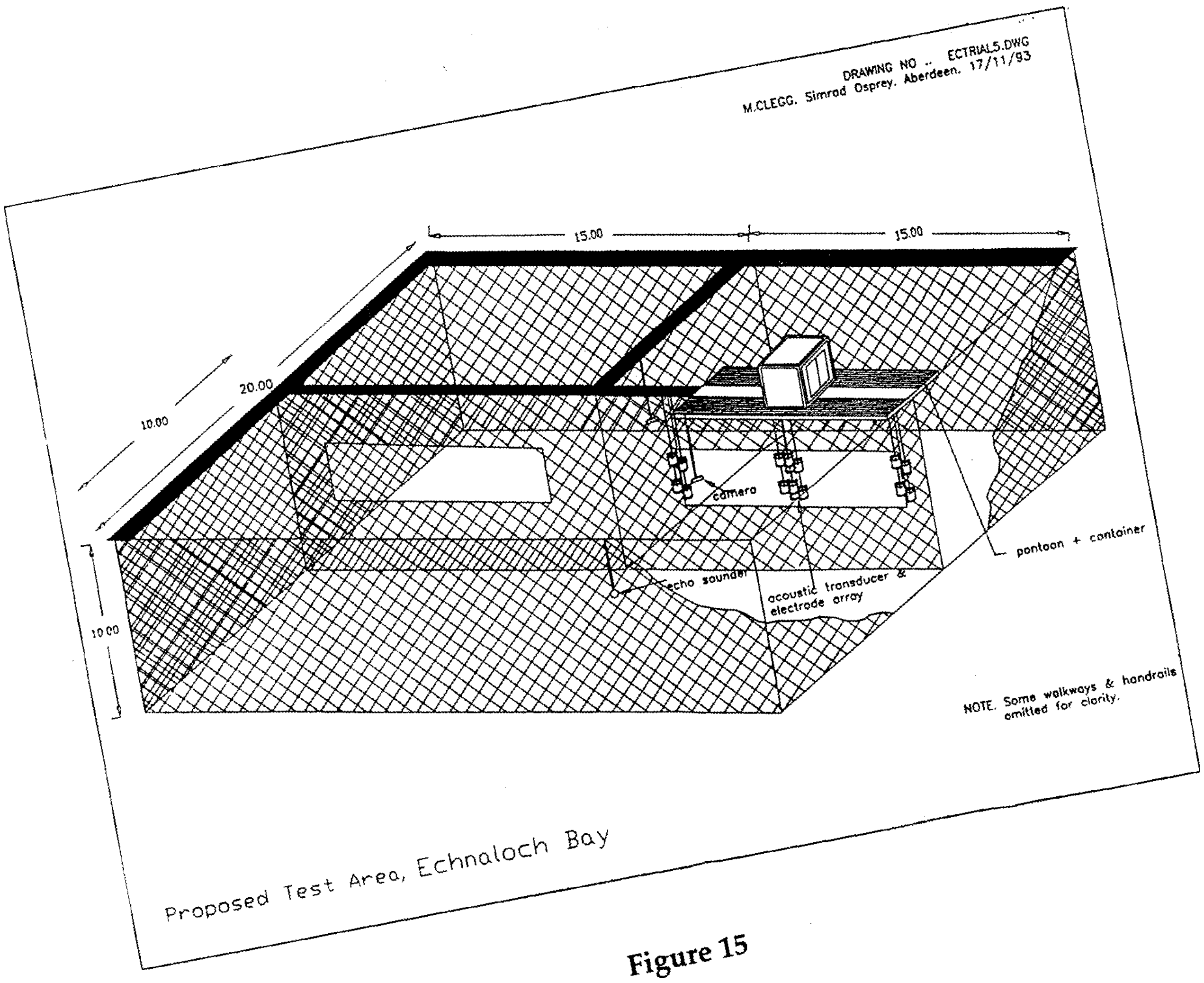


Figure 14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15.00
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camera
echo sounder
acoustic transducer & electrode array
pontoon + container
NOTE. Some walkways & handrails omitted for clarity.
Proposed Test Area, Echnaloch Bay

Figure 15

Infrasound: Atlantic Salmon in Norway and Pacific salmonids in the Umatilla River

Dr. Frank Knudsen
University of Oslo

First of all, I would like to thank the organizing committee for inviting me to come such a long way from Norway to talk to you today about our studies on the use of sound to scare fish. In Norway we rely on water power to produce our electricity. Although the sizes and number of our dams cannot compare with what you have in the U.S., they still constitute a problem to our Atlantic salmon in that the fish will swim into the water inlets of the turbines and will probably die. The estimated loss of outmigrating fish in our river systems is ~10%, quite similar to what you have here in the U.S. We have tried to develop a behavioral screen using infrasound, and I would like to define infrasound as any frequency below the audible range of humans, which is -20 Hz; in contrast, ultrasound is any frequency above the audible range of humans, which is ~15–20 kHz. We have called our project 'Use of Sound to Guide Juvenile Salmonids', and Olav Sand, Hans Erik Karlsen, Per Enger, and I are working on this. Per Enger has been investigating hearing mechanisms in fish since the late 1950s. He's retired but still very active in the group and in the field. Karlsen has been working a lot on infrasound detection in fish, and did these studies together with Olav Sand. My work in the group has been behavioral studies on the possible use of infrasound to scare fish.

Our first approach was a laboratory study that we called 'awareness reactions and avoidance responses to sound in juvenile Atlantic salmon'. Before performing these experiments, we needed information about what salmon can actually hear. Fortunately, there was already an audiogram available for Atlantic salmon that was published by Hawkins and Johnstone back in 1978. On the X axis we have sound frequency, and on the Y axis we have sound intensity presented as particle acceleration, which we now know is the adequate stimulus for the hearing organ in fish. This line is threshold sensitivity to different frequencies of sound. We can see from this audiogram (Figure 1) that hearing in Atlantic salmon is restricted to frequencies <380 Hz. The optimum hearing range for Atlantic salmon is -150 Hz. Hawkins and Johnstone (1978) measured the sensitivity down to only 30 Hz, so the hearing threshold below this frequency is calculated by us based on today's knowledge of infrasound hearing in fish. In our laboratory study, we focused on frequencies of 5-150 Hz. We were especially interested in including infrasound in this study, since it has been demonstrated that swimming fish, e.g., attacking predators, produce **a** lot of infrasound frequencies.

We were looking at the spontaneous response to sound, not the trained response used when you are establishing audiograms. The spontaneous response to a novel stimulus in animals is what we call the 'orienting response' wherein an animal alarms itself to a potential. danger. Behaviorally, the animal will direct its sense organs towards the stimulus source, and physiologically their pupils will dilate, there is a change in the EEG, their heart rate decreases, and their respiration becomes irregular. In our laboratory study, we were looking at this spontaneous response to two different frequencies of sound. In this experimental setup (Figure 2), we tested the reaction of salmon to sound. It is, in its simplest form, a metal tube with loud speakers in each end. The fish were confined in this tube between two electrodes that picked

up the electrical fields associated with their heart beats and with the respiratory movements. This signal was amplified, filtered, and visualized on a pen recorder or an oscilloscope as an EKG or the actual respiratory movements. We used a sine-wave generator to produce our sound stimulus so that both frequency and amplitude could be accurately controlled.
We see in the next picture an example of the response of salmon to sound (Figure 3). Here we have the EKG with the heart rate ticking along, here we have the breathing movements, and here we have stimulation with a fairly low intensity of sound at 10 Hz. You can see that the heart rate decreases and respiratory movements cease for a short while during sound stimulation. As I say, this was a low intensity of sound. By increasing the intensity, we quite often got this response. This is actually an electromyogram, indicating that the fish is swimming. So by increasing the sound intensity, the orienting response was released by activity.

These are some of the results from our laboratory tests (Figure 4). I have again plotted the audiogram for Atlantic salmon as a reference. We have frequency on the X axis and particle acceleration or sound intensity on the Y axis. We can see that for the infrasound frequencies <10 Hz, the sound intensity must be 20-25 dB above the actual hearing threshold before we get the spontaneous orienting response to sound. With increasing frequency, e.g., 150 Hz, the sound intensity must be 70–80 dB above the hearing threshold before we get the same orienting response. So with an increase in frequency, there has to be an increase in sound intensity to obtain the same response.

In this next figure (Figure 5), you can see the magnitude of the orienting response and habituation to a high and a low frequency. Again, you have the heart rate ticking along here, and this is 10 Hz infrasound stimulation, this is 150 Hz stimulation. The first thing we should note here is that the duration of the decreased heart rate is much longer to the infrasound frequency compared to the 150-Hz frequency. And looking at habituation, you can see that at 150 Hz sound stimulation, there was no response the second time we presented the sound stimulus; whereas at 10 Hz, it took five trials before the fish habituated.

So the conclusion to be made from these laboratory studies was the following: Infrasound elicited an orienting response at a lower intensity than sound; the magnitude of the response, or duration of the decreased heart rate, was always greater with infrasound than with sound; and habituation of the response was always slower with infrasound than with sound. Given this result, it was then interesting to go out in the field and look at responses to sound and infrasound in free-swimming fish in the wild, which was the topic of our next study in Norway that we called ‘Avoidance Responses to Low-Frequency Sound in Downstream Migrating Atlantic Salmon Smolt’. We picked a small river near Oslo to do this study, and we chose the frequencies 10 and 150 Hz. I will point out again that 150 Hz is in the optimal hearing range for Atlantic salmon. We used two sound sources: a commercially available sound source, the J-9, which was driven at 150 Hz; and a self-constructed infrasound source that was driven at 10 Hz.

This is a sketch (Figure 6) of the infrasound source which was, in its simplest form, a metal tube with a piston in front. This piston was driven by an eccentric coupling to an electric motor running at 600 rpm, which is the same as 10 Hz. This shows how the sound source was submerged in the water. This sketch of the observation site (Figure 7) shows where the river branches into a lower main course and an upper minor channel that rejoins the main course after -30 m. At the lower end of this channel, we installed our sound sources, and the numbers of fish reentering the lower main course were counted in alternating periods with and without sound. There were no observable effects on the smolts with 150-Hz sound. even at intensities 114 dB above the hearing threshold for this frequency. At an intensity 30 decibels above the hearing threshold, 10-Hz sound was the most effective deterrent to the fish which always showed a flight response by turning and leaving that channel, by panic swimming at the upstream branching point.

This table (Figure 8) shows the actual results from the infrasound test. What we have here is a number of test periods, this is the duration of each test period in minutes, and this is the number of fish reentering the main stream with and without 10-Hz sound stimulation. You can see that with 10-Hz sound stimulation, it was 0, 0, 0, 0, 1, 0, 0, 3, and 2. That totals 6 fish passing the sound source when it was running for a 170-min time-period. If you look at the numbers without sound, there were 57, 18, 47, 30, 29, 24, 17, 102, and 57 fish passing the sound source, totaling 338 fish in a 170-min time-period when it was not running. This illustrates the deterrence effectiveness of infrasound, at least at this small site. You can also take a look at the results from the 150-Hz test, exactly the same table (Figure 9): when 150-Hz sound was applied, 58 fish passed the sound source; without sound, 52 fish passed the sound source, illustrating that 150-Hz sound has no effect on the flight behavior in Atlantic salmon.

Given this result, it was of course interesting to test the effectiveness of infrasound in modulating behavior of Pacific salmonids. Last spring we came out to Oregon to do a study with Carl Schreck at Oregon State University on the effect of infrasound on modulating behavior in steelhead and chinook salmon. The title of this study is 'lnfrasound Produces Flight and Avoidance Responses in Pacific Juvenile Salmonids; the Use of Sound to Guide Fish'. Also Sue Knapp, who is head of the Fish & Wildlife Field Office in Hermiston, Oregon, did a lot of our field studies.

But first of all, as in Norway, we did laboratory studies at Oregon State University's fish facility, the Smith Farm. This is a fish tank, ~10 ft wide x 3 ft deep. You can again see the sound source, and we also used accelerometers, or kinetic hydrophones to measure the output from the sound sources to assure ourselves that we were stimulating the fish with infrasound and nothing else. The output from the hydrophone was visualized on an oscilloscope. We tested steelhead and two size-groups of chinook. We tested a total of eight groups of what we call 'large' chinook, and a group of fish were released into this tank for a couple of davs before we did the actual test. It is very important that the fish be given an acclimation period before doing these behavioral studies, because we know that very stressed fish will not respond at all to any stimuli. After this acclimation period, we started our actual test by turning on the sound source for 5 sec and turning it off for 15 sec, repeating this sequence 20 times. The fish were then given a resting period of 1 hour, and we did the same test again. It is very important to also study habituation to infrasound, because in a river system the fish might pass several hydropower water intakes as well as many irrigation intakes.

The result of this test was that we saw avoidance responses in all steelhead and chinook tested, very similar to what we obtained in Norway. Taking a closer look at the results from this test of infrasound, you can see that on the first five trials the fish would avoid the sound source with a startle response or with panic swimming away from the sound source. On the successive 15 trials, the fish would still avoid the sound source. So there was no habituation on this first test. Of course, this infrasound source is not ideal; it is a prototype and has to be improved. It's producing a lot of other frequencies than infrasound, and it also has a visual component from the piston movement. So to assure ourselves that these components did not contribute to scaring our fish, we did a series of small tests. First of all, we placed a metal disk in the tank and moved it so there was a visual stimulus. And there was no startle or avoidance response in the fish whatsoever. Next, we tilted the sound source up in the air, so all the other noise produced by the sound source could be freely transmitted **into** the tank or into the water. Again, there was no startle or avoidance response. Finally, we left the sound source in the tank and uncoupled the piston so that the motor was running and producing all those other frequencies. That also gave us no response at all. So our conclusion was that it was the infrasound component produced by the sound source that was actually scaring the fish. I have a video of the flight responses obtained from these tank studies that I can show you. In the laboratory study, we also tested the responses in species other than chinook and steelhead. This is a sucker which also responds with flight to infrasound stimulation. But when we tested the lampreys, they gave no response at all to the infrasound stimulation. So there is a species difference here.

Our next approach was to do a field study in northeastern Oregon where we picked this very small river, the Umatilla, which has two small irrigation intakes at our field-site. One headgate is closed and the other is open, and our sound source was mounted just in front of the open headgate. When we performed these experiments, the water level in the river was very low, so the farmers had installed dam boards to force the water, and consequently also the fish, over towards the irrigation intake. When the fish were approaching this area, they had two choices: either swim into the irrigation inlet, or swim down a fish ladder and reenter the river main stream, which is actually what we wanted, of course. Unfortunately, we did not obtain enough data scientifically from this field study, but we have done a couple of observations on behavioral responses. We always observed that as a group of fish was approaching the sound source, and we turned it on, they would panic swim away from the sound source. Hopefully we can obtain more results from this site, perhaps next year.

So the conclusion to be made so far from the Norwegian studies, and also our studies here in the U.S. is that it seems very possible to use infrasound as an effective fish deterrent, at least in irrigation canals. What has to be done in the future is obviously scaling up. We have to test infrasound at actual dams. Furthermore, there is a need to construct sound sources better than our prototype. And we have actually done that back in Norway. We have a new and improved prototype that is submersible, making installation much easier, and that has two opposing pistons. Our previous sound source had one piston that vibrated a lot when it was running, and that caused wear and tear on the sound source itself. With these two opposing pistons, the vibrations cancel each other out. Thank you.

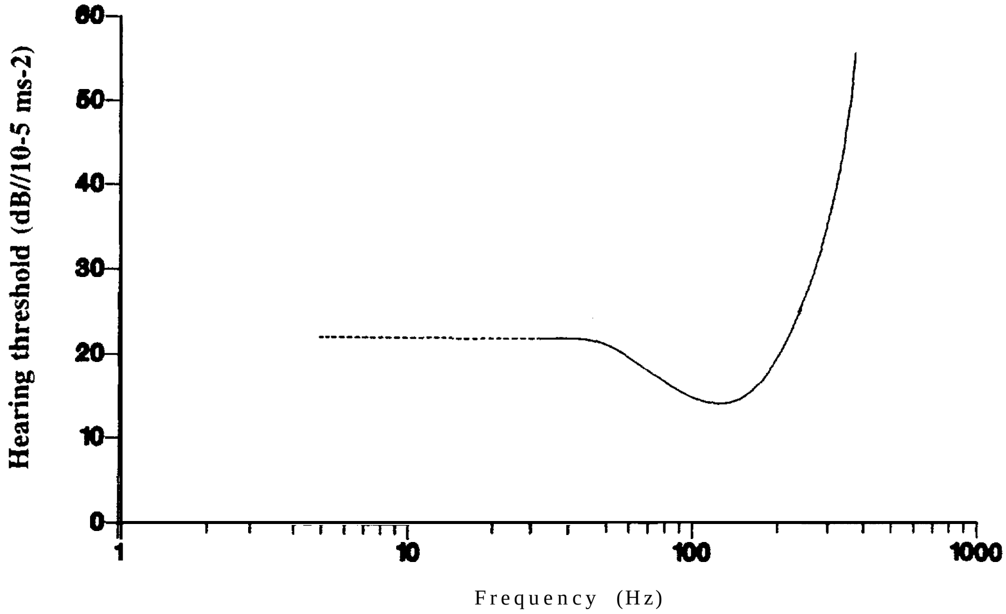


Figure 1
Acceleration audiogram for Atlantic salmon based on values from Hawkins & Johnstone (1978).
The hearing thresholds >30 Hz are estimated by extrapolations.

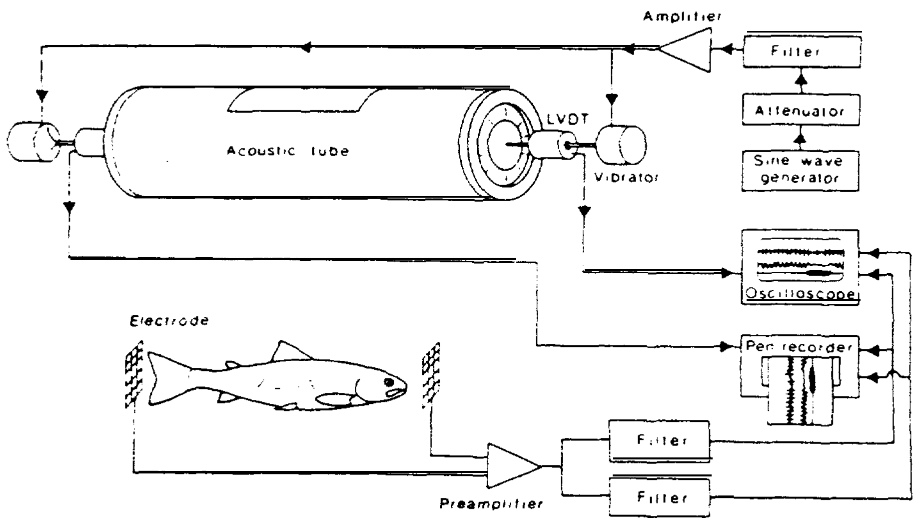


Figure 2
Experimental arrangement for studying spontaneous awareness reactions.
The 68-cm acoustic tube had a bore of 12 cm.

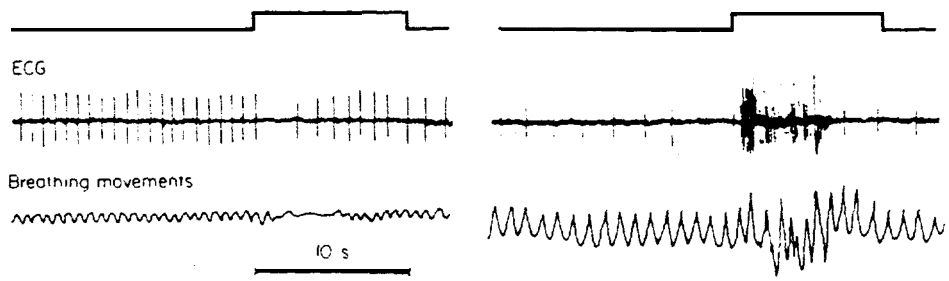


Figure 3

Spontaneous awareness reactions to intense sound. The left section shows bradycardia and reduced breathing movements in response to a IO-Hz tone. The recordings to the right show swimming activity evoked by a high sound-intensity stimulus. The upper traces indicate the presence of the sound stimuli.

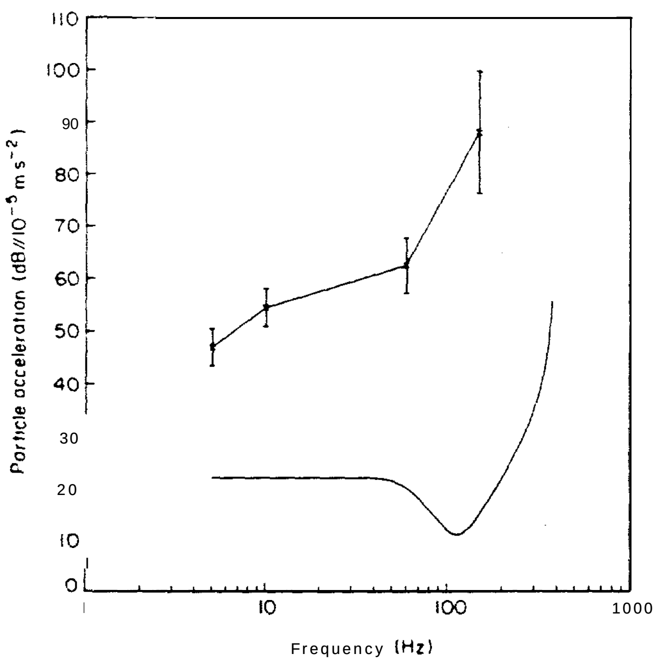


Figure 4

Spontaneous awareness reaction (x) thresholds for juvenile Atlantic salmon compared to the hearing thresholds (—) for this species. Values are given as mean ± SD, n=10.

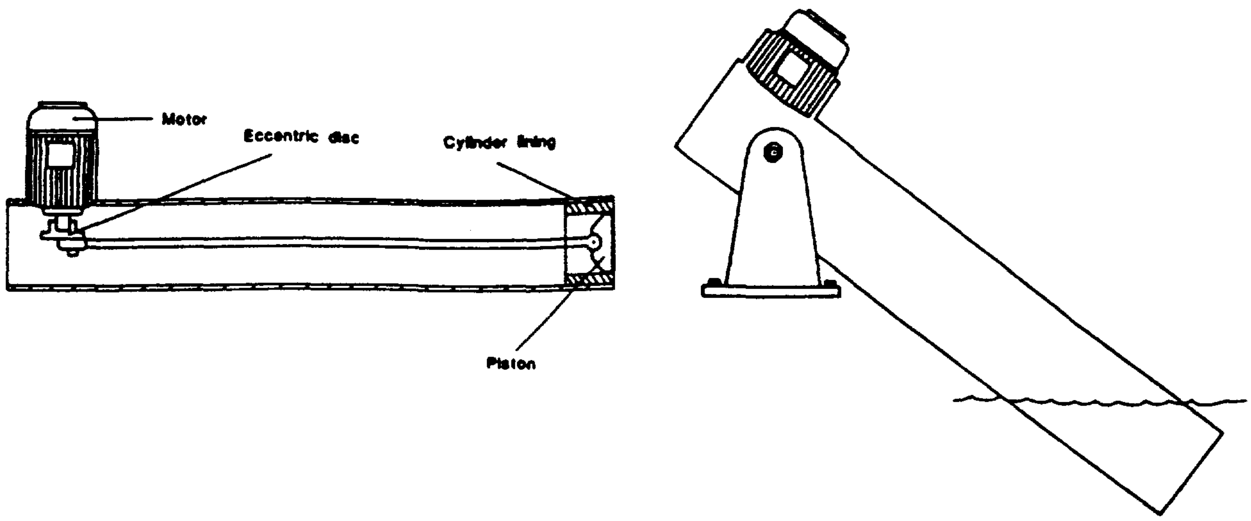


Figure 5

Two series of ECG recordings from the same fish comparing the habituation to 10- and 150-Hz sound stimuli repeated every 35 sec. Positive responses are indicated with asterisks. The upper trace represents the presence of the sound stimuli.

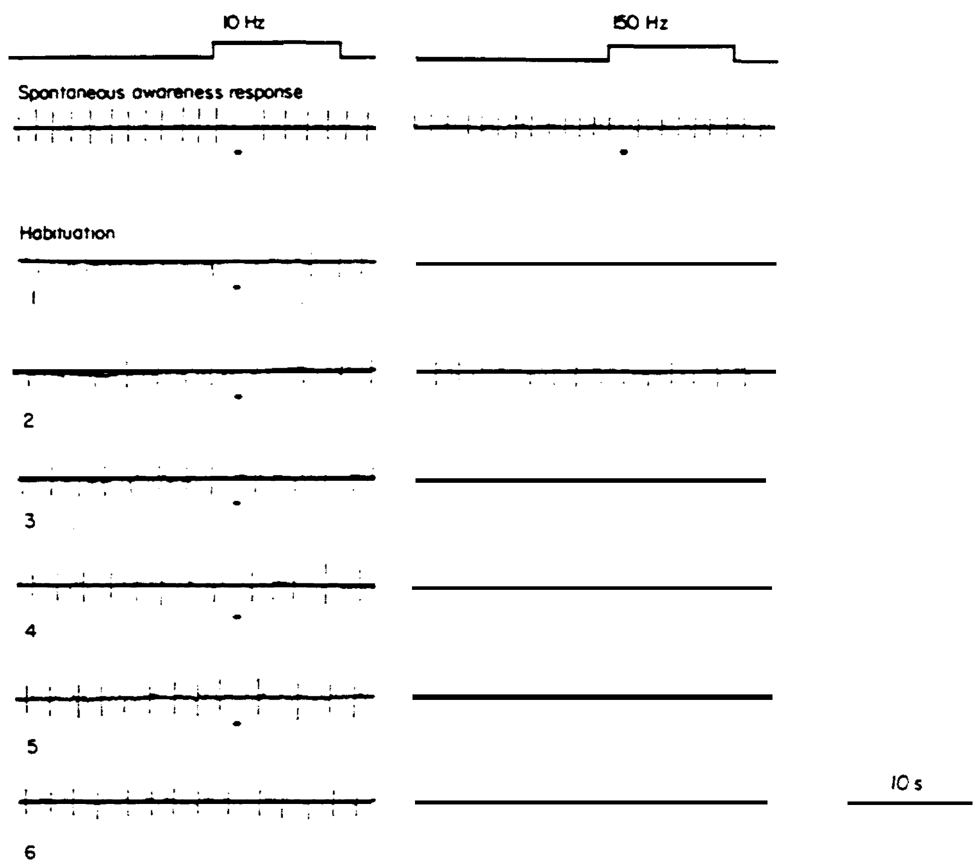


Figure 6

The sound source used to generate infrasound. See text for details.

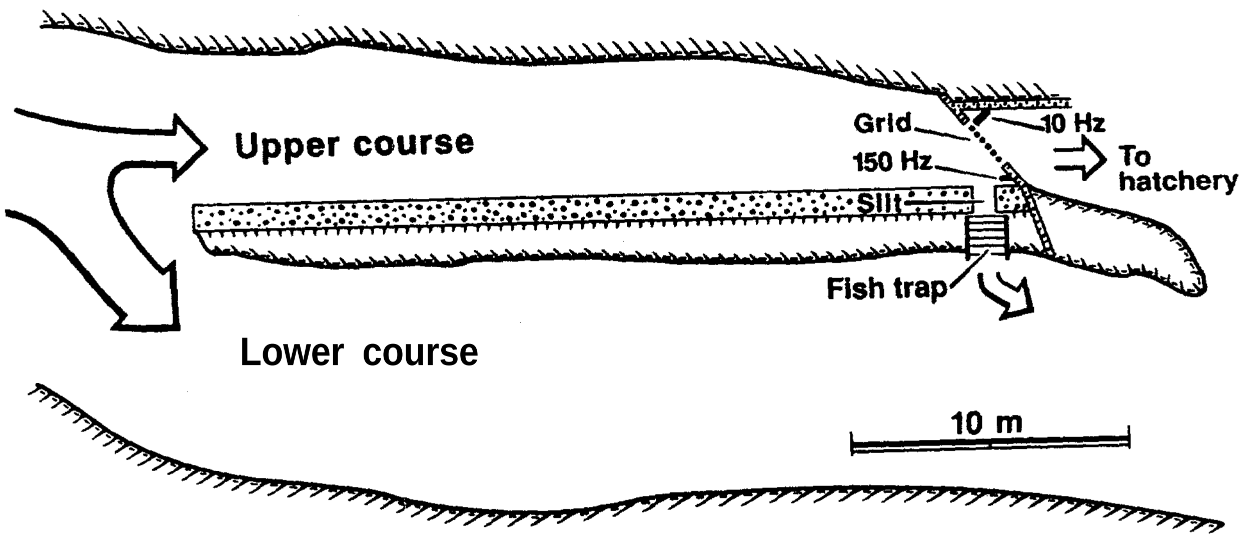


Figure 7

Sketch of the Norwegian observation site. Arrows indicate direction of water current. See text for details.

Period	Duration (min)	With 10 Hz sound		Without sound	
		No. of rounds	No. of fish	No. of rounds	No. of fish
1	20	7	0		
2	20			6	51
3	10	3	0		
4	10			4	18
5	10	4	0		
6	10			4	47
7	10	5	0		
8	10			6	30
9	10	6	1		
10	10			S	29
11	10	S	0		
12	10			6	24
13	20	3	0		
14	20			2	17
15	40	8	3		
16	40			8	102
17	40	6	2		
18	40			S	57
Sum	170	47	6	46	338

The number of swimming rounds in the channel indicates the total exploring and swimming activity of the fish during the sampling period.

Figure 8
Effect of 10-Hz sound on the number of smolts entering the mainstream through the side wall at lower end of the channel.

period	Duration (min)	With 150 Hz sound		Without sound	
		No. of rounds	No. of fish	No. of rounds	No. of fish
1					
2	10 10	3	11	4	18
3	10	2	3		
4	10			1	I
5					
6	10 10	2	2	2	0
7					
8	1010	1	2	I	I
10	10	3	8		
11	1010	4	6	3	4
12	10			3	4
14	10	2	2		
15	10 10	3	7	3	7
16	10			4	3
17	10	3	5		
18	10			4	3
19	10				
20	10	4	6	5	5
21	10	4	6		
22	10			4	6
Sum	110	31	Sa	34	52

The number of swimming rounds in the channel indicates the total exploring and swimming activity of the fish during the sampling period.

Figure 9
Effect of 150-Hz sound on the number of smolts entering the mainstream through the side wall at lower end of channel.

Question & Answer Session

DR. HASTINGS: I have a question for Frank Knudsen. How close were the salmon to the infrasound source before you saw the avoidance response? In your test, you said that once they approached the source, at some point they would startle and immediately swim away.

DR. KNUDSEN: Using this specific sound source with that specific output, you see avoidance responses --

DR. HASTINGS: 2.5 to 3 m?

DR. KNUDSEN: Yes.

DR. HASTINGS: So statistically we are well within nearfield?

DR. KNUDSEN: Yes.

DR. BROWN: Did you still use the 4-cm total stroke?

DR. KNUDSEN: No, we do not. This new sourceactually has a 6-cm displacement.

DR. BROWN: What about when you got the 2.5-m avoidance?

DR. KNUDSEN: That is the 4 cm.

DR. BROWN: This is for Mike Clegg. Did you take them out of the water before you smoked them? And did you say that the power output of your device was 120 watts?

MR. CLEGG: 120 watts electrical power output.

DR. BROWN: And what's the output power? 1%?

MR. CLEGG: I would say it's about 5%.

DR. BROWN: And what's the diameter?

MR. CLEGG: 200 mm.

MR. SCHILT: Is there some reason to think that little fish would be less affected by an electric field than bigger fish? Is there a size function to that?

DR. COOMBS: I'd like to address the question of fish size with respect to the lateral-line system. You heard me say this morning that the effective distance, or the working range, of the lateral-line system is within 1 or 2 body lengths. So shorter fish have a shorter distance range than longer fish. This is basically tied to interpore spacings on the lateral-line system that determine the kind of pressure-gradient pattern the animal will see. Perhaps tomorrow I can illustrate this. It turns out that the interpore spacing on the trunk lateral-line canal tends to be a constant fraction of the fish length.

We have studied this in about six different orders of fish, sampling different species. And that fraction, at least along the trunk, is about 0.01-0.02 of the standard length of the fish. Basically this affects the excitation pattern which encodes distance, such that when you get further away from the source, depending on the fish length, the excitation pattern becomes essentially' flat, meaning there is no information in the pressure-gradient pattern about the source location or its distance. I think this may be related to your finding and seeing only short fish getting enpenned.

MR. SCHILT: Of course, the smaller fish can cross bigger lines of potential because they only have that much to cross. The bigger fish are going to cross more lines and stand a greater chance of getting fried than the little fish.

DR. BROWN: The samplings shouldn't matter, providing it's small enough to resolve --

DR. COOMBS: I think it does. Let me show you tomorrow, because it requires several graphs to illustrate.

DR. BROWN: This question is for Mike Clegg. Did I understand correctly that, after all of this, something like 80% of the available fish got enpenned?

MR. CLEGG: Of the fish that were actually counted, 6 million fish were enpenned and they were fried. They weren't dead because there were 'on' and 'off' periods. At the end of the 14 days, there were 6 million fish that went through the barrier, 99.9% of which were shiner only 56 mm long. And so the effectiveness of the system was based on the fact that these small fish were going through it. Now, you can turn around and say that there were 6 million fish and 99.9% of them went through, and therefore the system doesn't work. But the fact that these fish that went through were only 56 mm long raises a question I have to ask. What happened to the rest of the fish that should have been there?

DR. BROWN: First of all, how do you know there were 6 million fish that went through?

MR. CLEGG: You had better ask the consultants that. They were counting them in the nets. At the end of the tunnels they had diversion chutes, and they employed half of the unemployed in Dunkirk to work shifts for about $2 an hour counting fish.

DR. BROWN: How do you know how many fish were sitting out there waiting to come in, in order to get a percentage of what went through? This is a large number of fish you are talking about.

MR. TAFT: If you were doing on and off tests, you should have had a comparison of numbers and sizes (system on vs. system off). If the big fish were there, you should have seen them during the off period.

MR. CLEGG: The big fish didn't appear at all. There were only 1 or 2 individuals that actually appeared. It was constructed such that the 'off' period was only for a maximum of about 6 hours at any one time. Because we are talking about Lake Erie-where there's no migration past the forebay opening and so we're really considering only resident fish here-they could just as well be sitting out in the harbor itself. Who knows what they were doing? But the 6 hours that they were 'off' may not have been a long enough time to do a proper control. Maybe they should have been left ‘off’ 24 hours to get a better control, maybe 12. Somebody had used a computer program to say statistically that this is what we should be doing, these are the times that it should be ‘on’ and ‘off’, and it was a random time-period that we were given. I didn’t select that, the consultant did. Afterwards, they extrapolated all these figures, using some fancy statistical analysis and boot-strapping, and said that this is the effectiveness of the system.

MR. TAFT: I would suggest that if there were bigger fish out there, you would certainly have seen them come in during a 6-hour period over many days given that the system was interacting with them in any way. If you didn’t see them, I’d conclude they weren’t in the area.

MR. CLEGG: We were looking only at the yearly impingement and count records for the four years prior to that. If you take the block where we were doing the test, then unless something dramatic happened to those larger fish in that year, why would they choose not to appear the fifth year? Who knows? We know that climatic conditions, lake temperatures, wind, and weather can make a difference, but that wasn’t addressed in the results of the trial.

MS. HARN: I have a question for John Menezes. Could you briefly describe the evaluations that were done for the ultrasonic system on the American shad juveniles?

MR. MENEZES: The system we used was essentially the same as at Fitzpatrick, from an acoustic standpoint.

MS. HARN: I’d like to know how you evaluate the effectiveness of the system.

MR. MENEZES: That was pretty easy. I have a video I’ll be glad to send you. It’s called the ‘popcorn video’ because, if you look at the fish bypass in the upper part of the water column, you see the fish go up on top of the pile dam and go back and forth, and you open up the fish bypass and see this enormous volume of water going downstream, and there are no fish going out. When you turn the system on, it’s like a lightbulb going out. You see fish popping out through the discharge in the water. They had people from RMC counting the fish, and I forget the number. But if you see the video, I don’t think there will be any question.

I have two questions for Mike Clegg regarding the Dunkirk demonstration. Did you determine the effective range of your transducer? And do you have beam patterns of your transducers so that you can say, I think this is good for x meters, and here’s what the beam patterns look like, and then come up with a transducer configuration? Before the experiment began, how did you convince yourself that you had the input, the intake?

MR. CLEGG: We did these models at the SINTEF facility in Trondheim in a very large ship-modeling tank. We took the results of that model and put that same installation into Dunkirk. The time-scale didn’t allow us to make comparisons between a model we did at Marintech and the real thing at Dunkirk. It was later, when we processed all this stuff, that we realized that modeling an acoustic barrier in a towing tank is not easy and does not marry up when you try to replicate it on site. So I don’t believe at this stage that you can realistically model an acoustic field and then conclude that this is how it will really work at the site. But we did that model in Marintech and then took it to the Dunkirk site.

DR. HASTINGS: At 10 Hz, your wavelength is 150 m. So the beam pattern that he is talking about and what you have are totally different things. You’re all in nearfield. So when you’re talking about formulating a monopole or a dipole, that's probably fine for what you were saying, for the location of the fish or for those sources. And you didn't measure out at 600 m?

MR. CLEGG: No, we would have gone over the breakwater to do that.

DR. HASTINGS: So the beam patterns I think are irrelevant.

DR. DUNNING: I think the work at Dunkirk points out or underscores the need for an adequate control when you're doing this kind of testing. Because the question really comes up, what was out there that didn't come through? And if there were a control you could point to and say, there were lots of big fish but we didn't get any, then your demonstration becomes a lot more rigorous.

MR. CLEGG: Yes, I think the evaluation and effectiveness of the system will require that a lot more work be done on that, as well as on the systems themselves. I think evaluation and effectiveness have to be incorporated into any system that's built, even for real in the site.

DR. DUNNING: This question is for Frank Knudsen. You showed us the results from testing smolts at 10 Hz, I believe, through two channels and with 31 rounds of sound on and off. Can you describe how those occurred in time, when the sound was on and when it was off?

DR. KNUDSEN: What do you mean specifically?

DR. DUNNING: Your slide showed the results of 6 fish total with sound 'on' and 36 with sound 'off'. My question is, what were the rounds that you had listed?

DR. KNUDSEN: The point was that when a group of fish came swimming down the river and entered the area in front of the sound source, they would then be swimming a little upstream again before they reentered the same area. And each time thev came down to the sound source, some of these fish would let themselves through the slit and into the mainstream river.

DR. CARLSON: A round would be an exposure, then?

DR. DUNNING: It sounds like it would be a replicate.

DR. KNUDSEN: But the problem during these field experiments was that the number of fish in the river was very, very low; so we had to take what we got.

DR. DUNNING: Did all of the sound-on tests occur before all the sound-off tests, or were they alternating?

DR. KNUDSEN: Alternating

MR. TAFT: Frank, as I recall from the laboratory tests, you did work in the tank where you subjected the fish to the piston, and they moved out a certain distance. I remember a plot of X's and O's. And I don't recall anything in the paper about a startle or flight response, only a moving away of the fish from the source. And yet in your field studies, you've described a very strong startle and a directional movement away from your source. I'm wondering what was different, if anything, between those two studies. How do you explain the difference in response?

DR. KNUDSEN: Always when you work out in the river, the response of the fish is obviously more pronounced. I think the main reason is that under laboratory conditions you're giving them a too-short acclimation period. They have a slight stress that is influencing the responses you obtain.

MR. TAFT: So the signal-to-noise ratio was different?

DR. KNUDSEN: It was very different.

MR. TAFT: And still you get more response in the field?

DR. KNUDSEN: Yes.

MR. TAFT: You attribute that to the fish coming in naturally and not being handled?

DR. KNUDSEN: Yes, I think so.

MR. CLEGG: For some of us, startle response means a very abrupt bending into a C shape that may well be mediated by the Mauthner cells. Maybe to others, a startle response means 'hauling buns'. So it might be helpful if we could agree on what we mean by startle response.

MR. TAFT: I heard two things: One was that there was a startle response, and the other response was directional which is your 'hauling buns'. In our studies, we've seen both responses.

DR. HASTINGS: I would like to follow-up on that question. Were you running that thing continuous-wave when you did the tests in the tank?

DR. KNUDSEN: Yes.

DR. HASTINGS: You were running continuous waves and your dimensions were 3 ft. by 10 ft wide. So at those frequencies, you are going to have standing waves. Certain fish could be located at places where there was no particle acceleration at all if, say, you were at a pressure antinode in the tank. So I wouldn't expect acoustically to get the same --

DR. KNUDSEN: It was definitely not ideal.

DR. HASTINGS: Because the difference in the acoustic field is that 10-ft. tank.

MR. SCHILT: I think some of the confusion is that in the laboratory, in those between the tanks, you get a startle response. That was observed usually during the first 5 or 6 --

DR. HASTINGS: Did you say that, Frank?

DR. KNUDSEN: The studies done here in Oregon were not those done in Norway.

MR. SCHILT: You can observe the startle response on the videos that Frank showed. It's sort of a flick of the tail.

MR. TAFT: Can I ask my question again? What was the difference between the tests done in Norway and those done in Oregon?

DR. KNUDSEN: I don't think there was any real difference. I have videos on the responses as well, and you can always compare them. I think you will see that there is no big difference.

MS. HARN: Sorry to keep dwelling on this, but in one of your slides you showed two responses: a startle response and an avoidance response. Would you define what you mean by startle and avoidance?

DR. KNUDSEN: We have tried to separate that more passive swimming-away from the sound source from the panicky abrupt response that you saw. But it can be difficult.

MR. TAFT: But it's directional in both cases?

DR. KNUDSEN: Definitely.

Low-Frequency Sounds: Salmonids in the Sacramento River*

Paul Novakovic
Paul Loeffelman
Energy Engineering Services Company (EESCO)

We've been asked to give you a report on the activities of EESCO in the Sacramento River. In 1992 we were asked by the Delta Mendota Water Authority to come up with a program that would help them alleviate an oncoming problem. Delta Mendota runs the federal pumping station and the canal that takes water from the Sacramento River downstate as far as Los Angeles. So they have quite a responsibility. They also represent the largest group of individual water districts. The problem was that they had winter-run salmon which were declared an endangered species, and as a result the District was allotted only a definitive number of incidental take at their pumping station. So they were searching for a way to decrease the number of winter-run salmon approaching their pumping station. We gave them a proposal in late '92, and in '93 installed a system at a point where the river separates. If you take a right turn, you go down to the ocean at San Francisco, 50 miles away. If you take a left turn, you're going to the delta and will end up most likely in a pumping station.

We decided to look at this whole thing with the idea of accomplishing seven goals toward our program. (1) Determine the client's goal and see whether we had the means of achieving that goal, carried out in various stages of meetings with the client. (2) Design a system based on our six years of research in this general area, a system that would satisfy the pertinent agencies. (3) Hold meetings with a total of about eight interested agencies, including the U.S. Bureau of Reclamation and California Department of Water Resources. The great thing I saw happening was that we tried up-front to educate all the agencies as to what we thought could be done. Soon a consensus developed wherein even the skeptics of behavioral barriers at least acquiesced to the idea of doing a test in 1993. (4) We then, of course, had to be concerned with funding which was provided by the Water Authority, who in turn received some federal and state funding. (5) We had to install a system on the river on a scale that had never before been done. Logistics began to play a major role. For example, the system could not obstruct boat traffic, so all our cabling had to be laid on the bottom and brought up to each transducer putting out the sound, which made up this barrier. (6) We got into operations and developed a control system which in the second year was even more refined. The test operations in '93 provided sufficient data to satisfy the client that the demonstration was achieving their goal. (7) On the basis of that '93 data, the Water Authority decided to purchase the system for the '94 program.

In '94, in addition to verifying the passage or non-passage of salmon smolts, the Water Authority authorized additional studies to satisfy the agencies on matters such as effects

* Note: The transcript of this presentation was only partially edited by the authors, and none of the slides referred to in the text were made available for this publication.

on upmigrating adults, effects on mortality from predation following exposure to our sound system, and concerns about another endangered species, the delta smelt. Extensive studies were done, and there is a '94 report which has not been fully published yet for probably bureaucratic reasons. From a technical standpoint, we experienced no operational failures in '94 on our system. We were able to develop software to enhance the use of our hardware so that today the client can completely control and monitor the system from a laptop, which one of the engineers has with him at all times. Additionally, they can monitor it from their pump station where they have 24-hour personnel.

A lot of this came at a very low price. We have spent as a company a lot of money in design and development, in the very research that Joan Harn mentioned earlier. It's been a question of how long you continue spending money in a field that has not evolved the way people thought it would five or six years ago. Hopefully there will be opportunities to gain greater acceptance of behavioral barriers so that the entire industry can move ahead. I'm getting to the tail end of my career and certainly would like to see this completed and accepted. We have had great acceptance by the agencies in California, based on the latest work during the '94 season and some additional work in early'95. They have all essentially signed off on this report. And although we perhaps did not achieve as high a result as we would have liked, which would be ultimately a 100% diversion efficiency, we feel that we have a good, solid, well-documented result.

Paul Loeffelman will give you the biological details, but it's important that I leave you with one message. You've heard a lot about the ability of fish to hear, but nobody has yet been able to tell me why they do the things they do in response to sound. Even in our own case, where we have had positive results with signals that may not meet the criteria of some other speakers here, we really don't understand why the fish behave as they do. So I will let Paul Loeffelman come up and perhaps give you a better feeling from a signal-development standpoint.

MR. LOEFFELMAN: As Paul mentioned, our successes at Georgiana in '93 and '94 were the result of a lot of previous work that I began in 1986. Many people in this room have probably seen some information we put out about our signal-development process. I would like to review that a little to give you a fuller appreciation of how we were able to achieve 75% diversion efficiency in '93 and 84% in '94 at Georgiana with the system that we had in place. Unlike the applied approach of using 10 Hz, we have gone in a different direction, essentially using the concept of communication between fish. (Next slide) This began in 1985 when I was working at this hydro on the Ohio River, which is now completed. As a biologist I was trying to figure out why the fish that I thought should be going through this hydro were not. As it turned out, (next slide) we determined that at the Racine facility the special and fairly unique bulb turbines were creating a kind of sound with a signature that probably had something to do with the receptors in fishes that caused them to avoid the facility. Not all fish did this, however. And in anticipation of FERC requirements and the Clean Water Act at our steam facilities, I was interested in trying to figure out why this was happening and to make some progress in the area of using sound where it could be applied at our facilities.

So I read all the literature I could, I tried to understand a lot of what was discussed yesterday on the basic research, I looked at the way sound had been applied before.

And I concluded from my review that because things were so variable out there, there were so many unknowns, I couldn't go with an arbitrary signal that I thought would work everywhere, I couldn't understand enough about individual species because we've got a couple hundred of them across the American Electric Power System, from Michigan down to Tennessee. I needed another way to try to customize signals I thought would help move fish.

And hence we came up with the idea that perhaps by using the concept of communication between fishes, where one fish is making calls that presumably another fish is set up to receive, we could then use the clues from those fish calls to create artificial signals that would do the job. And by changing some of the characteristics, we would be able to cause the fish to move in a reliable, consistent, replicable way. (Next slide) So I spent a long, long time sitting in a boat looking through TV cameras, trying out different signals, doing fish calls or recording fish, analyzing their sounds with a spectrometer, and trying to relate the calls to the kinds of signals that I tried. And eventually some clues began to emerge from just sitting there and watching the fish do their thing over time. And that allowed me to begin a process of determining that if a particular fish call looks like this, this particular signal would seem to do the job.

Part of our process was to get good fish calls, and we developed a simple way of taking a portable recording studio wherever we needed help in sound, essentially just a large bag of water with some fish in it and a hydrophone, let them swim around and talk to each other (next slide). We found that fish preferred to talk to other fish, not to themselves. So we decided that loading a bag with more than one fish was the ideal. And as it turns out, many of the things that David Mann was talking about yesterday – the kinds of fish calls and when they made them – have been borne out by our auditions of many different kinds of fish. In fact, almost 100% of the fish we have auditioned have made calls for us.

With the understanding and the experience we have developed using the correlation between fish calls and the kinds of signals that would work, and the kinds of patterns and frequencies that we rejected, we began to understand the kinds of complex signals that would most likely work best in causing fish to avoid sound fields in a predictable way (next slide). Once we moved off the Ohio River, anticipating that regulatory agencies would probably have an interest in one or two species at those facilities, we began to refine this process so that we could say to an agency, we think we've got a good way of moving your fish of interest, so let us kev in on that.

As the first small-scale demonstration, the Michigan Department of Natural Resources let us test our process in a fish ladder with upmigrating steelhead and chinook salmon. The concept here was to temporarily stop the upmigrants from passing a counting station, so they would have to pass the speaker array. Through lots of sound-on, sound - off, over the entire run, which ran for a couple of months for three seasons, we determined thatsteelhead, for instance, were stopped at a rate of 72%. Wc felt that this was helpful and encouraging of the way we were developing our process.

One of the key aspects that we talked about yesterday was knowing the sorts of sound fields that you're dealing with. And in all cases, we've tried to go out and actually measure what the sounds look like to the fish. And in this case (next slide) you can see how we changed the acoustic environment of that fish ladder. It was a concrete fish ladder with standard pools. You can see on the sound-off that there is quite a difference with the rushing water cascading over the tops of the ladder, compared to the signal that we put in water. Again, I must remind you that this is not a steady tone, it is not one frequency. It is a complex signal, usually made up of multiple frequencies in a pattern that creates this different kind of look.

We were encouraged enough by those results to move upstream and attempt to move downmigrating steelhead and Chinook smolts at one of our facilities (next slide). The concept here was to try to put sound in this area at the entrance to the hydro, to essentially tell the fish, don't go right, go left. If you go left, you're going to Lake Michigan and you'll grow up and be happy. So we did a lot of work here, trying to understand the acoustics in this kind of river environment, developing signals for the steelhead and the smolts that were coming down. And we worked up a sampling regime that would drive us to the next level with this small scale and determine if we could actually move the fish.

So we put steelhead in the recording studio and developed a signal for those guys (next slide). They came downstream, we had sound-off, sound-on for the entire run, 12 hours on, 12 hours off, through the run time-period. And with capture nets below, downstream of the sound field, we achieved 94% diversion with steelhead. (Next) This is the sort of spectrum we're capable of putting out with the kinds of hydrophone and equipment we're using. It gives us pretty precise information about the kind of call we're looking at. Typically, we get multiple calls that we can use. Some are garbage, in my view; some are not biologically important, as we discussed yesterday; some seem to be more important and more predominant. A lot of these calls are consistent in their replication.

We changed the acoustic environment in this area, as you can see here, with the measurements we've taken (next slide). Again, it's a complex signal that was in the water, and this is what the fish were seeing. In the rivers that we've dealt with, you're usually looking at 80 or 90 dB. It's fairly flat across the spectrum. And the sorts of changes that we're producing in a localized way are fairly dramatic, e.g., for the chinook that were coming downstream, we achieved ~82% diversion at this project. On the basis of these successes, we were asked to provide a proposal to the folks running Georgiana, and went ahead in'93 with this kind of information. As I mentioned, we achieved 75% diversion.

The concept here (overhead) was to divert the fish from left to right. The folks at Georgiana and the agencies were concerned that our sound field would impact the up-migrants, stripers and chinook that were coming through. So we purposely had to leave a hole at the end of the line of speakers, just in case we were going to affect these folks. The objectives here were three-fold in '94. First, to move the fish past Georgiana in a way that would show positive guidance, which we were able to do. The average diversion efficiency was running ~60%, because of the hole there, as well as because of the flood tides that affected this particular site on the Sacramento. The second objective was to determine if we would affect the upmigrants; and through tagging studies, they determined that upmigrants were not affected by our signal. The third objective was to look at any adverse affects, and some of yesterday's questions about long-term delay mortalities and other physiological impacts were addressed and deemed not to be a problem here. For instance, they incubated Pacific herring eggs as a surrogate for the endangered delta smelt, exposed the eggs for 60 minutes, observed them for 312 hours, looking very carefully for sublethal effects, and found none.

So from **the** standpoint of adverse effects, the agencies are pretty well convinced that there shouldn't be **any** that they can't live with. The agencies also are happy with the diversion at this site given the practical challenges of boat traffic and flood tide. Also, they took great pains to design this study in a way that would provide very accurate instrumentation for temperature, flows, as well as statistical testing. All the agency people got together and came up with about 32 different statistical tests they wanted to run, and the numbers bear out what we had hoped, **that** we did actually provide some positive guidance for these fish.

Question and Answer Session

DR. SCHRECK: I'm curious about fish calls. Do you have any idea what they're calling?

MR. LOEFFELMAN: I think David Mann had a long list. They remind me of birds. We get chirps, thumps, knocks, clicks. They're very audible with the right kind of equipment. We have looked at some adults. We put a male and female, for instance, in here and got the courtship calls that people have been talking about. I don't always know what biological purpose they serve, I don't understand the language yet, but they do make them.

DR. NESTLER: So salmonids make courtship calls?

MR. LOEFFELMAN: Yes. From what work we have done, yes.

DR. SCHRECK: What size fish were these?

MR. LOEFFELMAN: In Michigan, these adults were on the order of 3 ft. We have also put little guys in there. The smolts make sounds, as well.

DR. POPPER: Do you have any tapes of the sounds that we could hear?

MR. LOEFFELMAN: I don't have any tapes with me right now. I also teach kids in school, and I tell them if you put your lips together and buzz them, bzzzzzzz, that's what a drum sounds like. If you want to be a smolt, you'll cluck like a chicken, cluck cluck cluck cluck cluck cluck cluck.

MR. MEYER: Ed Meyer with National Marine Fisheries Service. I know that you installed the system out at Bonneville Dam. Could you talk about your experiences with that for last season?

MR. LOEFFELMAN: The report's not even written yet. We are very careful about making sure that the relationship we have with clients is preserved.

Acoustic Fish Guidance: United Kingdom and European Experiences

Dr. Jeremy Nedwell
Subacoustech Ltd.

Dr. Andrew W.H. Turnpenny
Fawley Aquatic Research Laboratories Ltd.

DR. NEDWELL: I'm Jeremy Nedwell, and I'll be presenting this paper on the U.K. experience as a double act, with my colleague Andy Tumpenny of Fawley Aquatic Research Labs. Before we start, I'd like to tell you a little about the way we work together. Andy works primarily on the fish biology, as he has for many a year. My specialty is underwater acoustics. Subacoustech Ltd. provides specialist consultancy mainly to the U.K. Government. I believe I'm right in saying that we're currently the only specialist consultancy in underwater acoustics in Europe. Andy and I have been working together on fish deterrence for quite a few years now. Recently we received a Small Firms Award from the government for a research and technology scheme for fish deterrence. As a result of that, we've formed a joint-venture company to exploit some of the advances we've made in Fish Guidance System (FGS). And this talk will be presented largely in the context of FGS.

We entered this several years ago, and there are a few things I've learned about fish guidance which I'm sure are not new to anyone here (Figure 1). In my opinion, previous systems have been relatively ineffective. They tended to be very ad hoc; they took a speaker, threw it into a lake, and hoped that something would happen. There's a problem with the reliability of sources. Nothing has been designed specifically for the application. Fish are only sensitive to particular sounds, and the knowledge on that, as we know very clearly from the discussions yesterday, is far from complete.

The last item on the figure, and one I would like to address in the first part of the talk this morning, is the sound field. It's very apparent to me that no previous attention has been paid to the sound field generated in the water, despite the fact that sound fields in water have very different characteristics than the sound fields that we're used to experiencing in air. I would like to talk about this.

Let me start by explaining some of the applications of these systems that we've been looking at. This (Figure 2) is the Dunalistair hydroelectric station in Scotland. Here is the dam. It is a fairly old station, built in the early '50s. The flow from the dam is taken down to a generating house through an aqueduct which passes to the left side as you can see. There is a fish pass on the right side of the dam which takes less than 1% of the water. The interest here was in using acoustics to "thread the needle" and try to deflect downmigrating smolts toward the fish pass. You can just see the buoys on the surface. Here is another picture of these (Figure 3).

In this particular system, there were 64 projectors (Figure 4), actually supported by buoys, along a line which is an angle to the current, deflecting the fish towards the fish pass. This is the “acoustic rapier. ” We are trying to use this to guide fish precisely. The other example 1’11 give you is the acoustic ‘blunt instrument.’ Both of them have completely different needs in terms of the sound field. With the Dunalistair application, there is a very large number of small projectors -6 inches across which handle 50 watts. They are pretty rugged, they survive quite happily underwater for a long time. Because we were deploying them in large numbers, they are relatively inexpensive, and they are disposable. They are permanently sealed; if they break, we throw them away.

So why should we use acoustics with these systems? (Figure 5) The philosophy is this: We want to do as much of the work as we can before we actually hit the water with any equipment. We would like to preplan things as far as possible. We use an acoustical model to determine the optimal number of projectors and where they should be. So we move the projectors around on the computer and look at the sound field that we get. Where we find a suitable place to install them, the system will be installed. Then, in fact, we retrospectively use the sound model as well. We measure sound levels in contours around the installation and look at them from a biological standpoint as to whether they are achieving the needs of the system; and if necessary, we’ll go through that process again. Obviously, we would like to get it right the first time, but in practice that is not normally the case. There are usually refinements that can be made. So underpinning this is the availability of a suitable acoustic model.

The requirements are rather unusual (Figure 6). The model needs to be broadband and able to cope with propagation over at least the hearing range of fish, which, as discussed, is up to 2 kHz. It needs to be able to cope with shallow water. In the U.K., some of the systems we’ve looked at have been in very, very shallow water, sav 0.5–5 m. The model must be able to deal with complex geometries, e.g., sloping seabeds and riverbeds. Also, the projectors are frequently put in the vicinity of scatterers, such as jetties. And ideally, we would like the model to be able to cope with complex signals, the sort that are actually used. Finally, we haven’t time to put every bump and every lump in the riverbed, and every point of geometry into the model. We really want something that gives us a “broad brush” answer: Is it good or is it bad? So trom that point of view, we’re interested in putting in mean geometric features and getting mean results.

In fact, we use what is called a time-domain, ray type model, usually abbreviated the TR model. It’s worth saying (Figure 7) that there are 100-plus sound-propagation models that have been developed for the military that are of no use for this application. Many of them are used retrospectively; you measure the sound field, and lo and behold, if you tweak a few knobs, you can get the model to agree to the sound field. Thcy are of no use whatsoever in the predictive role, and are generally suitable only for water of depth ≥200 m. And of course sonar systems use single-frequencv operation, and so these models typically will deal only with single frequencies.

Input parameters (Figure 8) include the geometry, the depth, the state of the tide, the angle rake of the seabed, and whether there is hard rock or soft sediment. Local scatterers- spheres, cylinders, flat surfaces-can be included in the model. People like to think of the surface as a perfect inverting scatterer, but in fact the rough surfaces around here on the rivers will not perfectly reflect acoustic energy. We will have to take that into account in the model as well, and we can process a range of signal types. The computational load goes up if the signal is more complex.

To tell you a little about the physics of this. If you take a source in shallow water, sound energy arrives at a distant point by a range of paths (Figure 9). There is a direct wave, a seabed-reflected wave, a surface wave, and there are also multiply-scattered parts of the sound as well. These can actually be modeled in this particular model by taking the extra pathways and representing them in terms of image sources. Some of these are inverted with respect to the original and tend to try to cancel those, and others are in phase. It's rather like an optical problem of modeling reflection. The water surface is the reflector in this case. So, we have a set of sources. In this model, they're all effectively firing off waves.

I was very pleased to see Mardi Hastings show a figure very similar to this, which is much beloved by the acoustics fraternity. I started working with explosives, and that's why I've used the exponential pulse. But the principle is the same. The wave from each of these sources may look like this (Figure 10) at the source, or any one of the image sources. In propagating, the wave is delayed; there's a time delay, and it's also reduced in amplitude. The model sums many, many reflections, typically 50-100 million pairs to achieve an answer. It takes a long time to converge, but converge it does. This one equation (Figure 11) just says that the final wave that we get in this model is actually the sum of all these image paths. For those of you who work in acoustics, you will have seen that before.

As an example, I'd like to talk about a nuclear station, Hartlepool Nuclear Power Station. This is an example of a "blunt instrument," where the interest is in scaring fish away from the cooling water flow, something on the order of 200 m^3/s, a pretty major flow, which entrains fish. My colleague Andy will-talk about that later on.

Just to give you a little of the geometry of the place, this (Figure 12) is the Seaton Channel. There is a small tributary on the side of it. The cooling water is drawn in through an inlet channel dredged into the mud. This is exposed in low water, and the mud banks are exposed as well as the inlet channel at very low water. At high water, and most of the intermediate phase, the water actually comes up to the concrete wall. On the other side of the channel is Seal Sands; in fact, the year we installed the system, seals bred successfully for the first time, and there was very great interest by the environmental lobby who requested that we demonstrate no adverse effects on the seals. They were obviously keen to see positive effects on the fish.

The actual system was installed using relatively large projectors (Figure 13). These are another sort of projector that we use. They are high-powered and can run up to 600 watts. We tend to drive them at -300, because the reliability is enhanced. In this case, they were dropped just in front of the trash rack in the station. We also used projectors out to sea, and these were in a simple steel frame carried out to sea with a cable attached and dropped underwater with a buoy to retrieve it, if required. The system was driven from dry land. This was one of the equipment racks (Figure 14), with the signal-generating system at the top. You can actually switch through different signals to get rid of habituation, if that is a problem; there is a set of power amplifiers to drive the speakers.

And so to the modeling. This is an acoustical model (Figure 15), and what I have done here is to overlay it on the geometry of the projectors that we used for this particular model in the inlet channel. The geometry is this: The sea wall runs, if you like, along the back here, and you can see I've drawn a section of this where the inlet and a set of speakers are situated. The power station is just behind the wall. This is actually the inlet channel dredged into the mud. At about this point, about two-thirds of the way, the channel merges into the main water channel. At extreme low tides, the inlet channel is actually uncovered. If we have speakers only at the inlet wall, they wouldn't have any effect on fish being drawn into the inlet channel. It would be a one-way trip for the fish. For that reason, we also had some outlying speakers, and their only purpose was to protect the inlet to the dredge channel at extreme low water. And you can see a sound field that we have calculated above. But I'll talk you through some more interesting examples.

If you could keep that geometry in your mind when you are looking at these sound pressures, it will help to interpret the plots that I am going to put up. Sound pressure is the vertical axis overlaid on the region where the sound occurs. As an example, this (Figure 16) is low frequency, 100 Hz. It's calculated in this case for mean high water. You can see that near the inlet there's a high level of sound, a fairly uniform field. Also, where the speakers are used to protect the inlet to the channel, there's a high-level of sound as well. In fact, we found that the background noise level in this application is pretty high, -130 dB, basically because of noise from the cooling-water pumps. So the regions over which this works are everything above -30 dB.

If we now step up to a higher frequency, 400 Hz, with everything else unchanged, you can see a feature of sound propagation in shallow water (Figure 17). The higher the frequency, the greater the spread of the sound. So now in fact a very large region is being covered by the sound, both in the inlet speakers and the ones that are at the sea wall. But you can see the penalty that you pay for this: we are starting to get regions where there's interference. That's even clearer if you move up to a higher frequency (Figure 18). You can see here that there's very strong interaction. This is a feature of sound underwater, and it's one of the things that is missed very easilv. Sound underwater interacts with the water surface. The water surface flips the phase of it, and that means there is the abilitv for sound to be cancelled. That doesn't occur in air, and that's one of the reasons thatthese sound fields are so complex. You can see that sound is spreading out very well now, and in fact it is at a high-level, well above 130 dB, over the whole of the inlet channel. However, there are regions now where we have destructive interference, which is trying to reduce the level.

And part of the skill of using this sort of model is to ensure that those regions are where you want them to be, and that will become clear when I show you some of the bad examples. We also have to consider the effects of water depth. Here you can see an identical calculation, but this time it's for shallow water, 7 m, as opposed to 17 m at high water (Figure 19). And you can see that there is greater interference and a greater spread. There is a clear difference, depending on the state of the tide, and we have to look at that as well.

What would happen if we got it wrong? This is where it starts to get interesting. This was actually one of the runs that we did on this program. The idea is very simple. We thought, rather than having all the headaches of installing the high-power projectors on the seabed, couldn't we simply suspend them from buoys, because it's very easy to install. We put them in the water, drag an anchor, and that's the end of the story. And the answer is, no, you can't do that because these speakers actually interact with the water surface, and it leads to degradation in the field. You can see very clearly in Figure 20 that there are regions in very deep interaction with the wave, very great nulls in the sound field, where there's very low level. And generally the picture is of a sound field that is very complex: some areas high, some areas low. It may or may not achieve its objective, but obviously it's an additional risk that we wouldn't want to take.

Here's an even worse example (Figure 21). This is where the projectors have been placed on either side of the inlet in clusters. It makes them easy to maintain because you can pull six or eight speakers up in one go, rather than having to have individual runways to pull the things up. But you can see the penalty that you pay. Very high sound level results near these clusters, but we now have a far-field, which has very strong nulls in it. Now, picture this. If you're a fish coming into this, one reaction that you might conceive the fish would have is to follow the region of low sound pressure. This fan extends out in all directions. Under those circumstances, the fish will actually be guided into the inlet by the null in the sound field. So you can be in a situation where you achieve exactly the opposite of the desired aim of the system. That is why I think it is very important to try to look at the detail of the sound fields before these things are actually installed.

We are also looking at other systems at the moment. I will briefly mention this because this is the system that was funded by the government awards. We are looking at linear transducers (Figure 22) where we generate sounds along a line. Thev have some advantages where you trv to guide fish; rather than using individual projectors, it would be nice to generate sounds along a predetermined line, where you can place these things on a bed. This particular device is unusual, and we are currently going through the patenting process. It produces a sound wave, but the advantage is that the wave can't actually propagate. We can actually generate a very high sound level above the array, extending for several meters, typically ~160–170 dB. This is a non-propagating field, and it's interesting that the sound levels drop extremely rapidly away from this (Figure 23). You can see that in fact the levels have dropped by an order of 30 dB only 0.5 m away from this array, a very, very rapid change in sound field. My colleague will talk briefly about the initial applications of this device.

In summary (Figure 24), the 'time-domain ray type' model that we have introduced is particularly suited for this application and is accurate. It is a design tool that we think makes for efficient installation and the best use of resources, and which can also be used for fine-tuning systems for peak performance.

- Sound as a means of repelling (and attracting) fish is an old idea.

Systems previously ineffective because:

- Systems very "ad hoc"
- Sound sources very unreliable — not designed for a hostile environment
- Fish are sensitive only to particular types of sounds at particular frequencies
- No attention whatsoever to sound field in water

Figure 1

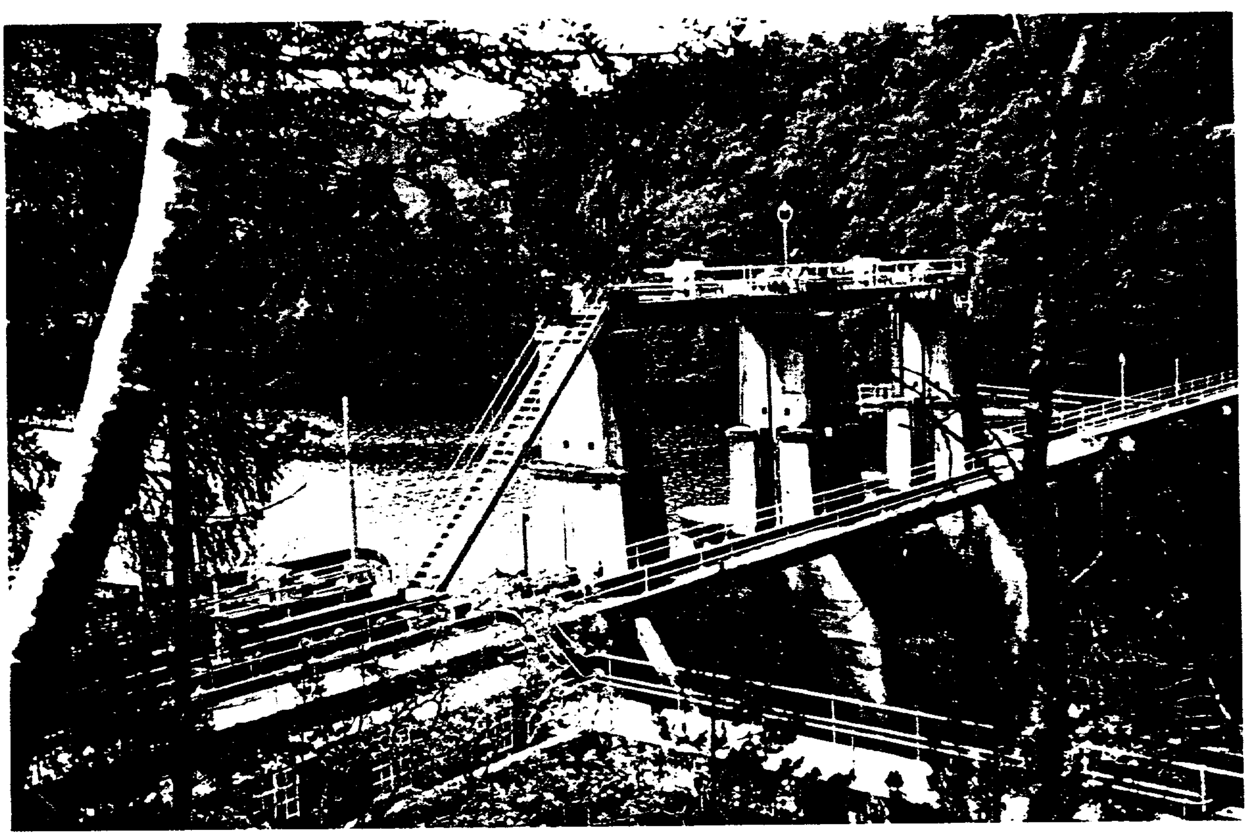


Figure 2

Figure 3

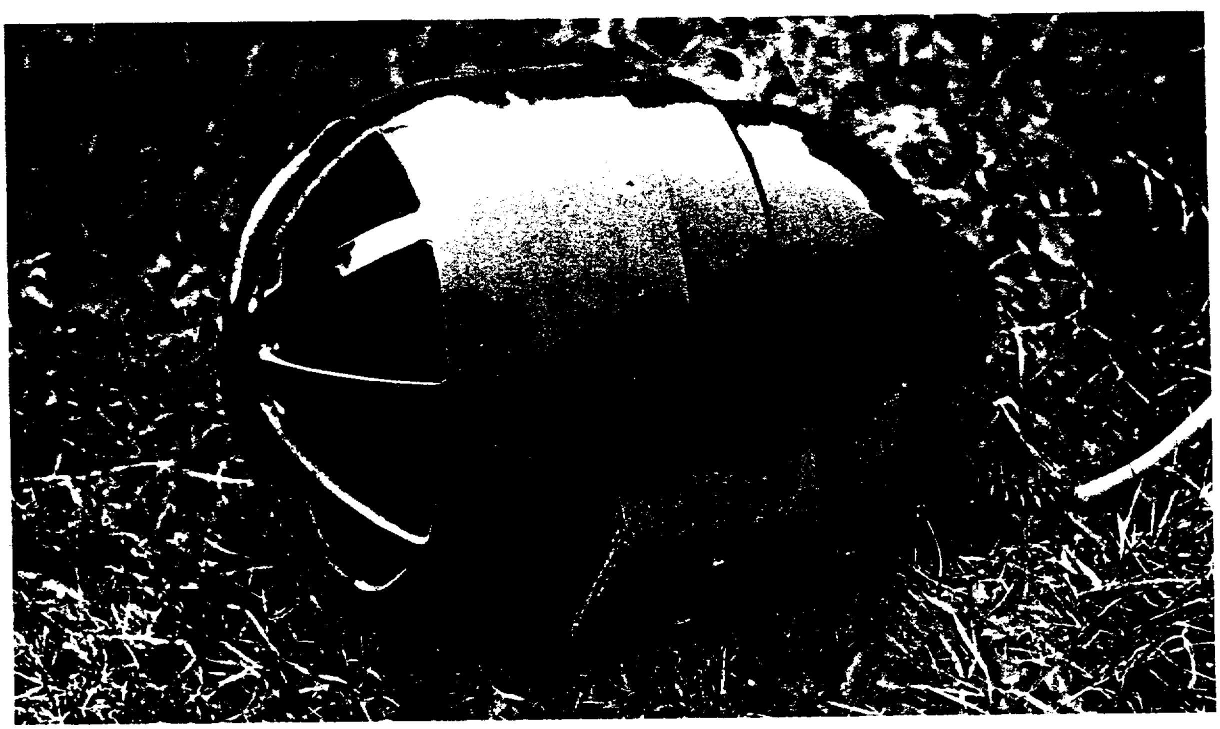


Figure 4

Philosophy of Acoustics:

1. Use acoustical **model to determine optimal number** and placement of projectors

2. Install system

3. Measure sound levels and contours around installation

4. Interpret in terms of likely and measured efficiency of installation

5. If necessary, refine layout and repeat process

Figure 5

Requirements for model:

1. Broadband and able to cope with propagation over at least the hearing range of fish (1 O-2000 Hz)

2. Able to deal with shallow water **(0.5-50** metres)

3. Able to deal with complex geometries, especially sloping river or sea beds and local scatterers such as quays, jetties etc.

4. Ideally, also able to deal with complex broadband signals

5. "Broad brush" features more important than accuracy

- implies Time domain, Ray type model.

Figure 6

Basis of acoustical model:

- I 00+ models of sound propagation developed for military interests

- Not of any use for this application since:

1. Require the input of many physical parameters

2. Only suitable for deep water > 200 metres

3. Single frequency only!

Figure 7

Input parameters:

1. Geometry (location of projectors)

2. Depth (tide state). angle of rake and type of seabed

3. Location of local scatterers

4. Surface conditions

5. Signal type

Figure 8

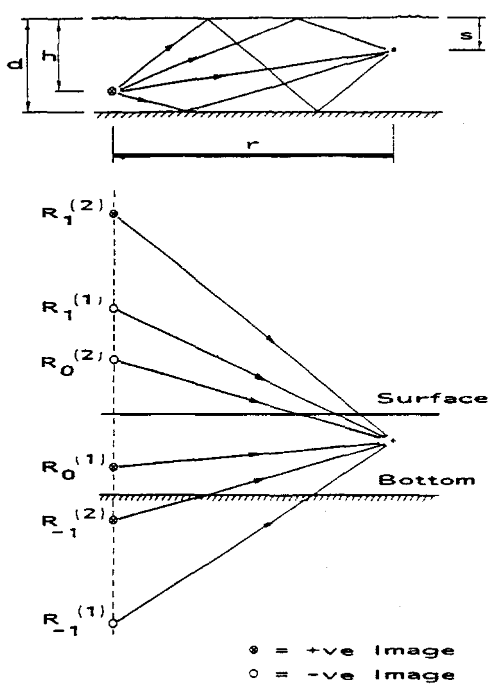


Figure 9

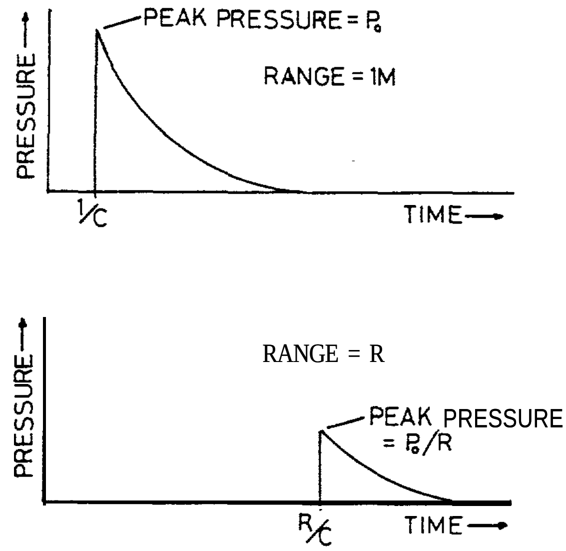
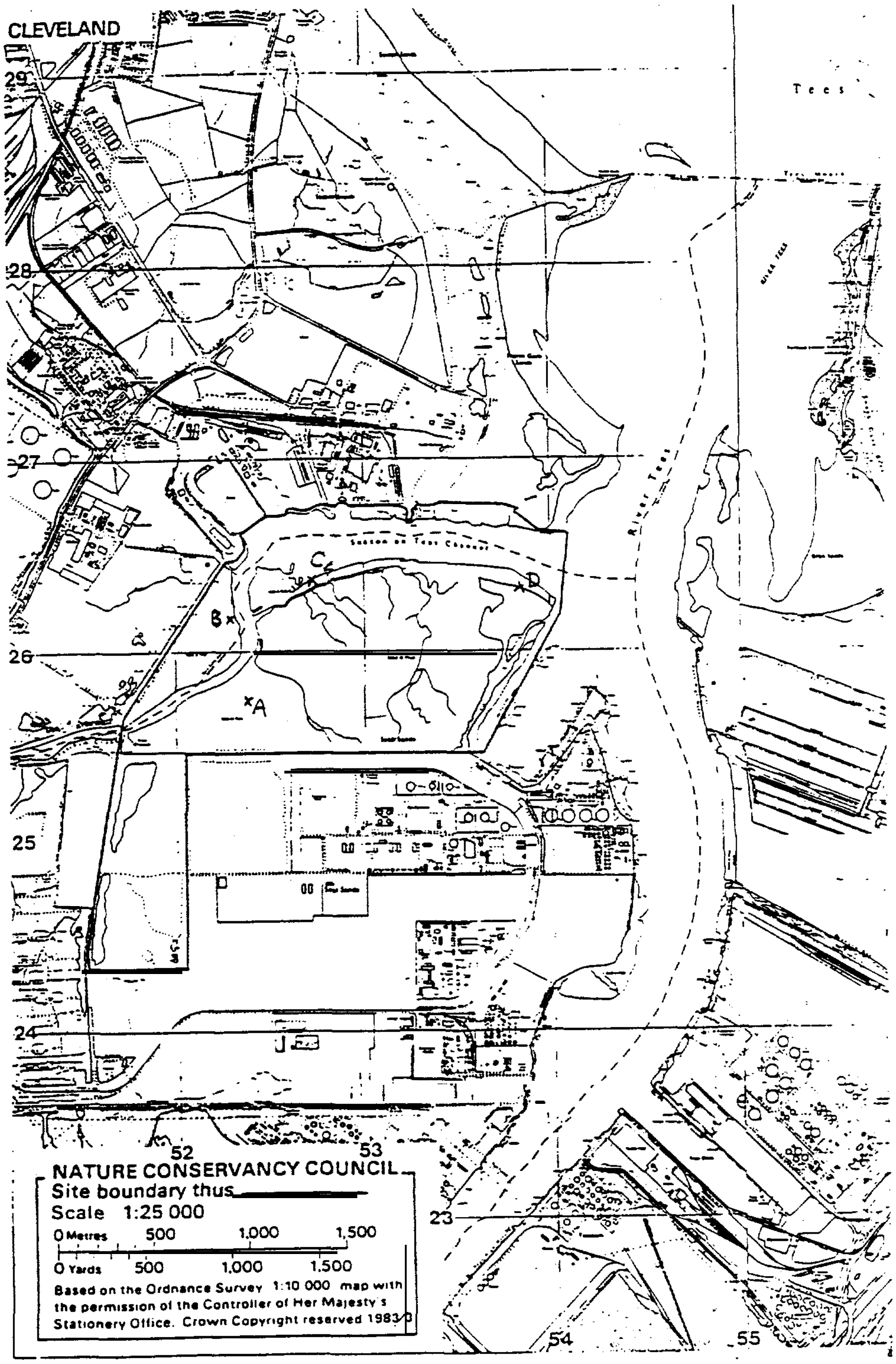


Figure 10

Assuming linearity, the waveforms may be superimposed and thus the total pressure is given by

$$P_T(t) = \sum_{n=-\infty}^{\infty} \Delta^{|n|} \left\{ \frac{(-1)^{|n|} \, p\left(t - \frac{R_n^{(1)}}{c}\right)}{(R_n^{(1)})^{\varepsilon}} + \frac{(-1)^{|n-1|} \, p\left(t - \frac{R_n^{(2)}}{c}\right)}{(R_n^{(2)})^{\varepsilon}} \right\}$$

Figure 11


CLEVELAND
Tees
River Tees
29
28
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NATURE CONSERVANCY COUNCIL
Site boundary thus
Scale 1:25 000
0 Metres 500 1,000 1,500
0 Yards 500 1,000 1,500
Based on the Ordnance Survey 1:10 000 map with the permission of the Controller of Her Majesty's Stationery Office. Crown Copyright reserved 1983

Figure 12

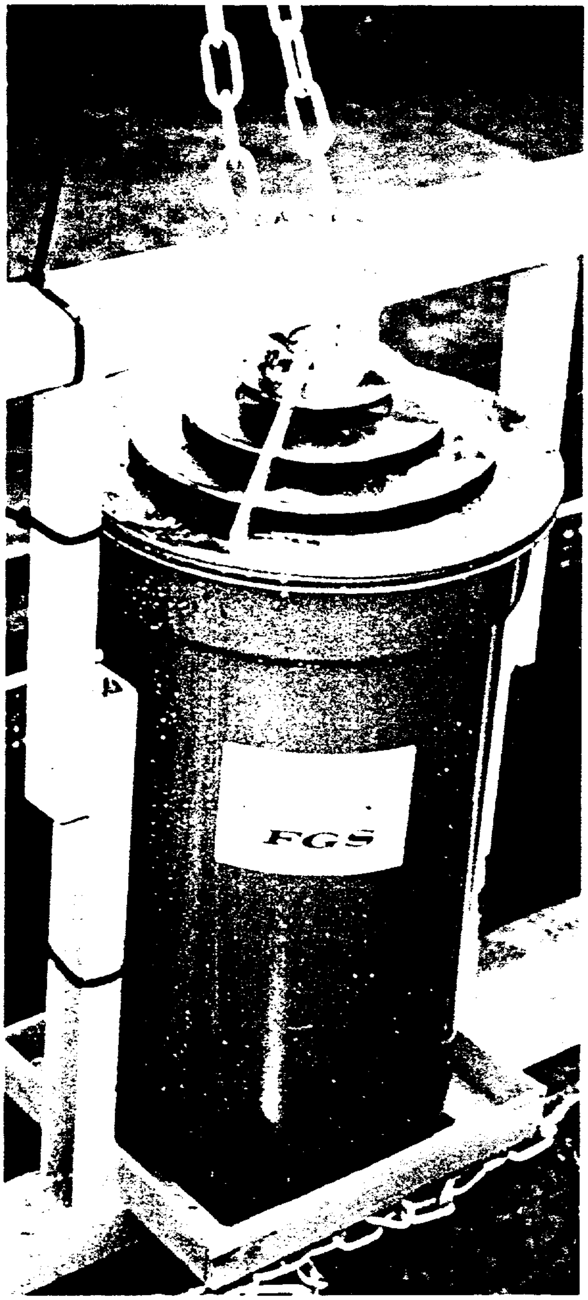


Figure 13

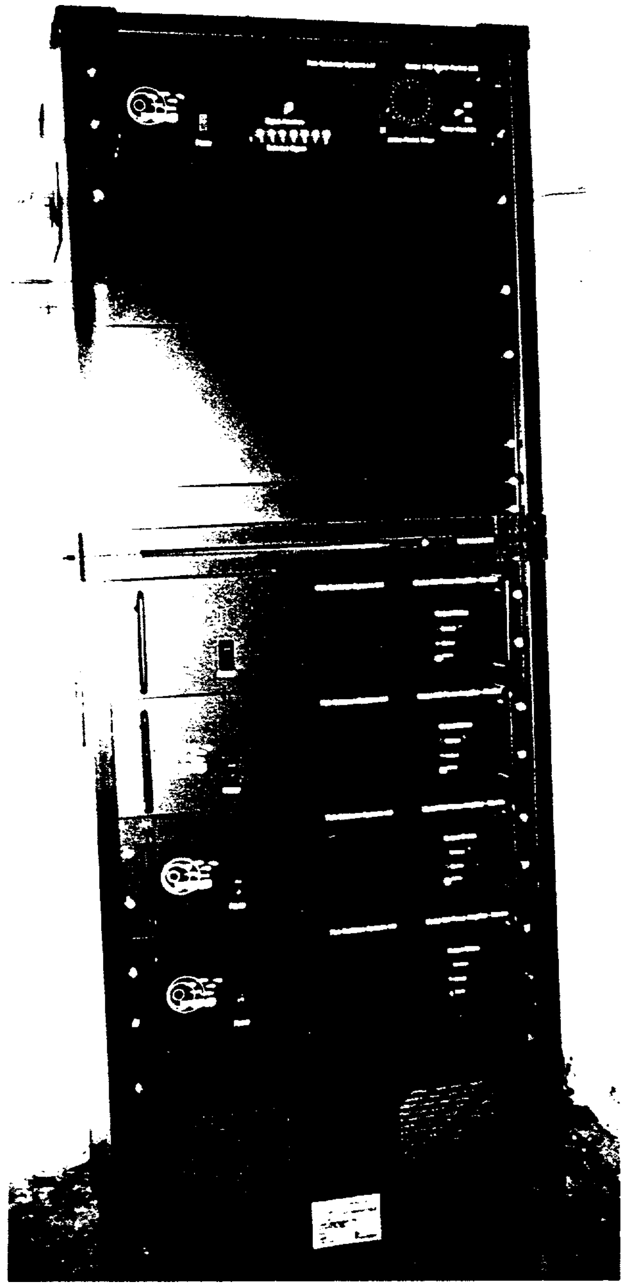


Figure 14

Sound Level Contours for a Twelve-Unit SPA System Using the PRISM Model
Mean High-Water Springs Frequency : 400Hz

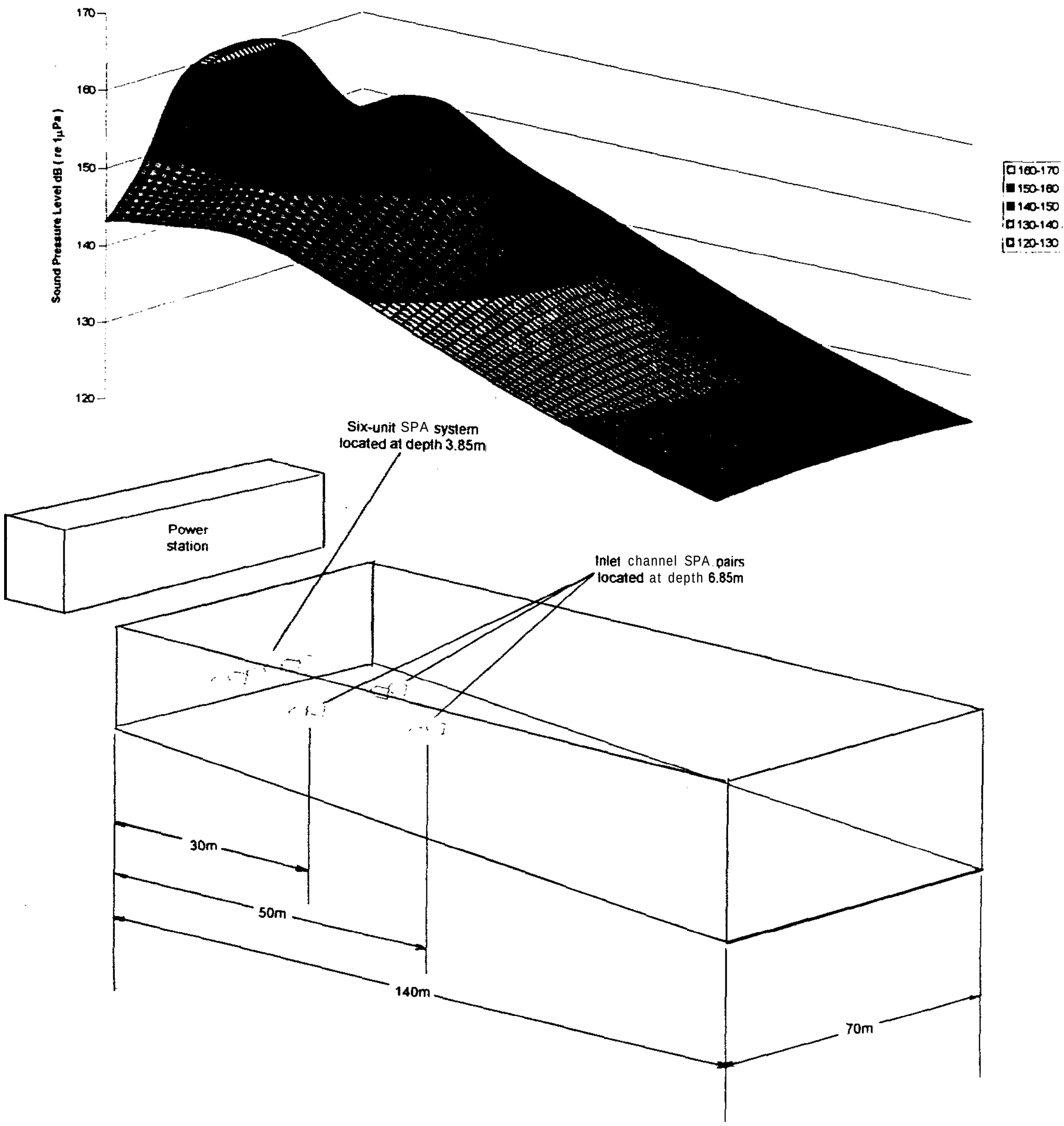


Figure 15

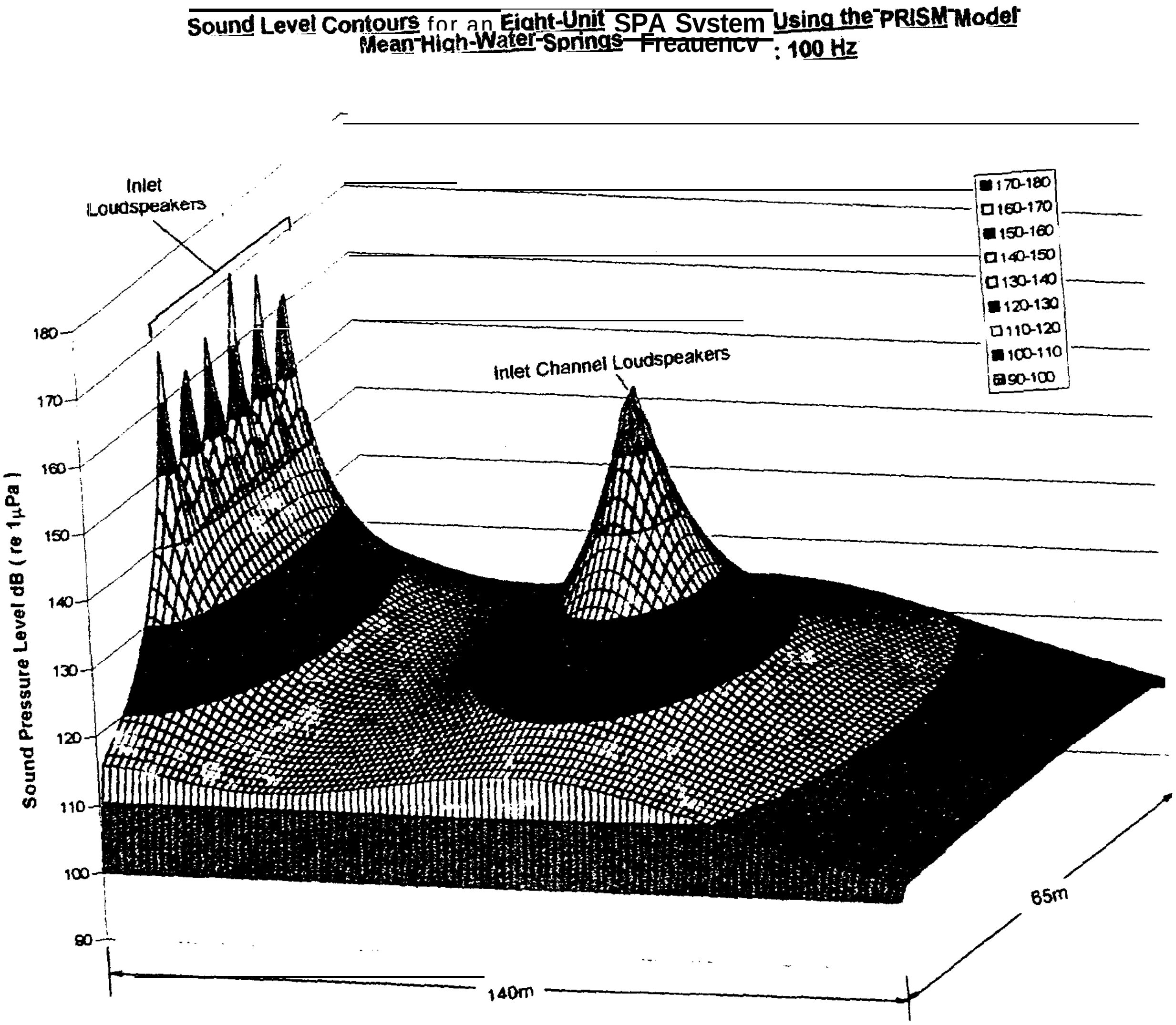
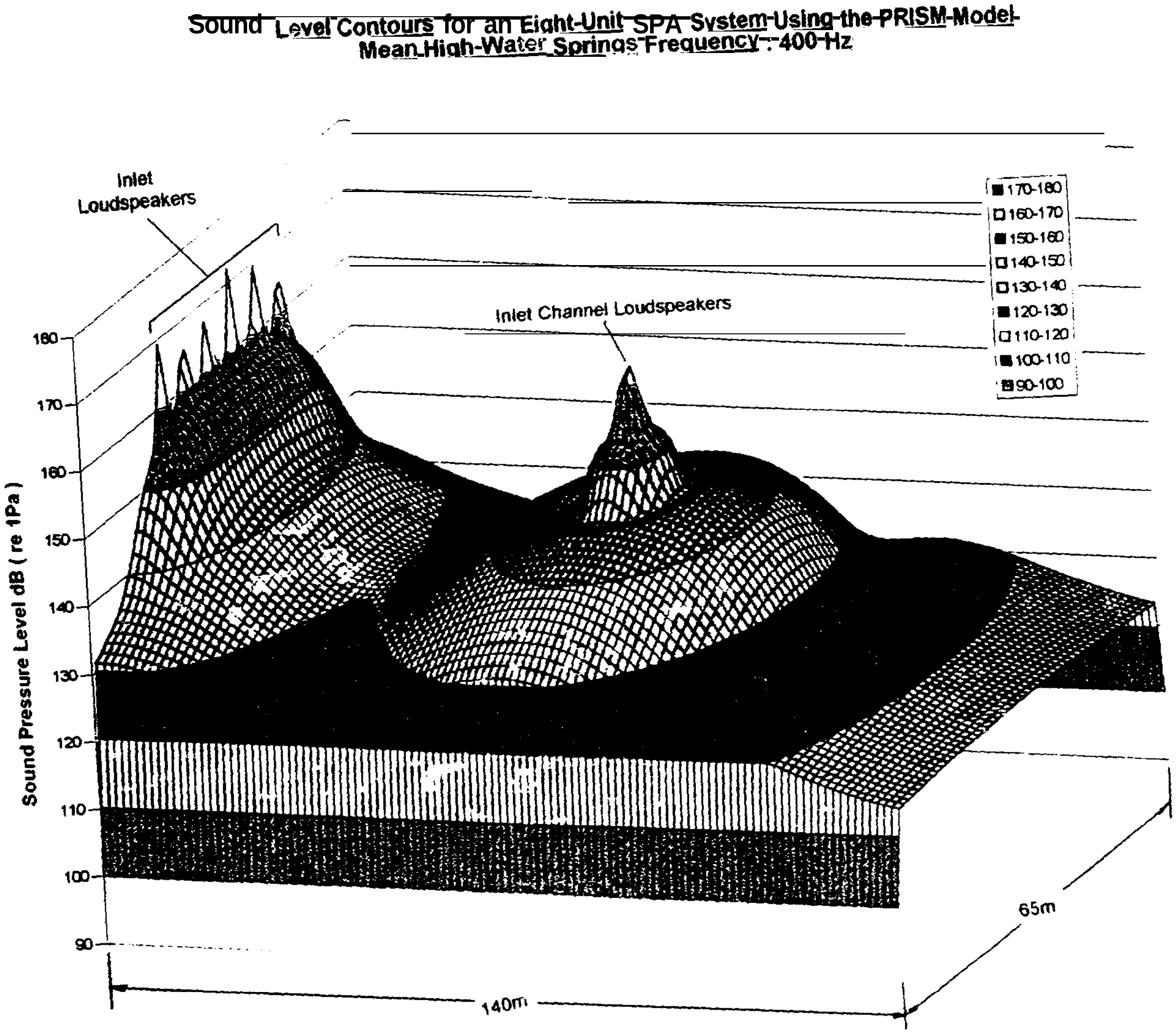

Sound Level Contours for an Eight-Unit SPA System Using the PRISM Model
Mean High-Water Springs Frequency : 100 Hz
Inlet Loudspeakers
Inlet Channel Loudspeakers
Sound Pressure Level dB (re 1μPa)
180
170
160
150
140
130
120
110
100
90
170-180
160-170
150-160
140-150
130-140
120-130
110-120
100-110
90-100
140m
85m

Figure 16



Sound Level Contours for an Eight-Unit SPA System Using the PRISM Model
Mean High-Water Springs Frequency : 400 Hz
Inlet Loudspeakers
Inlet Channel Loudspeakers
170-180
160-170
150-160
140-150
130-140
120-130
110-120
100-110
90-100
Sound Pressure Level dB (re 1Pa)
180
170
160
150
140
130
120
110
100
90
140m
65m

Figure 17

Sound Level Contours for an Eiaht-Unit SPA Svstem Usina the PRISM Model
Mean High Water Springs Frequency : 1 kHz

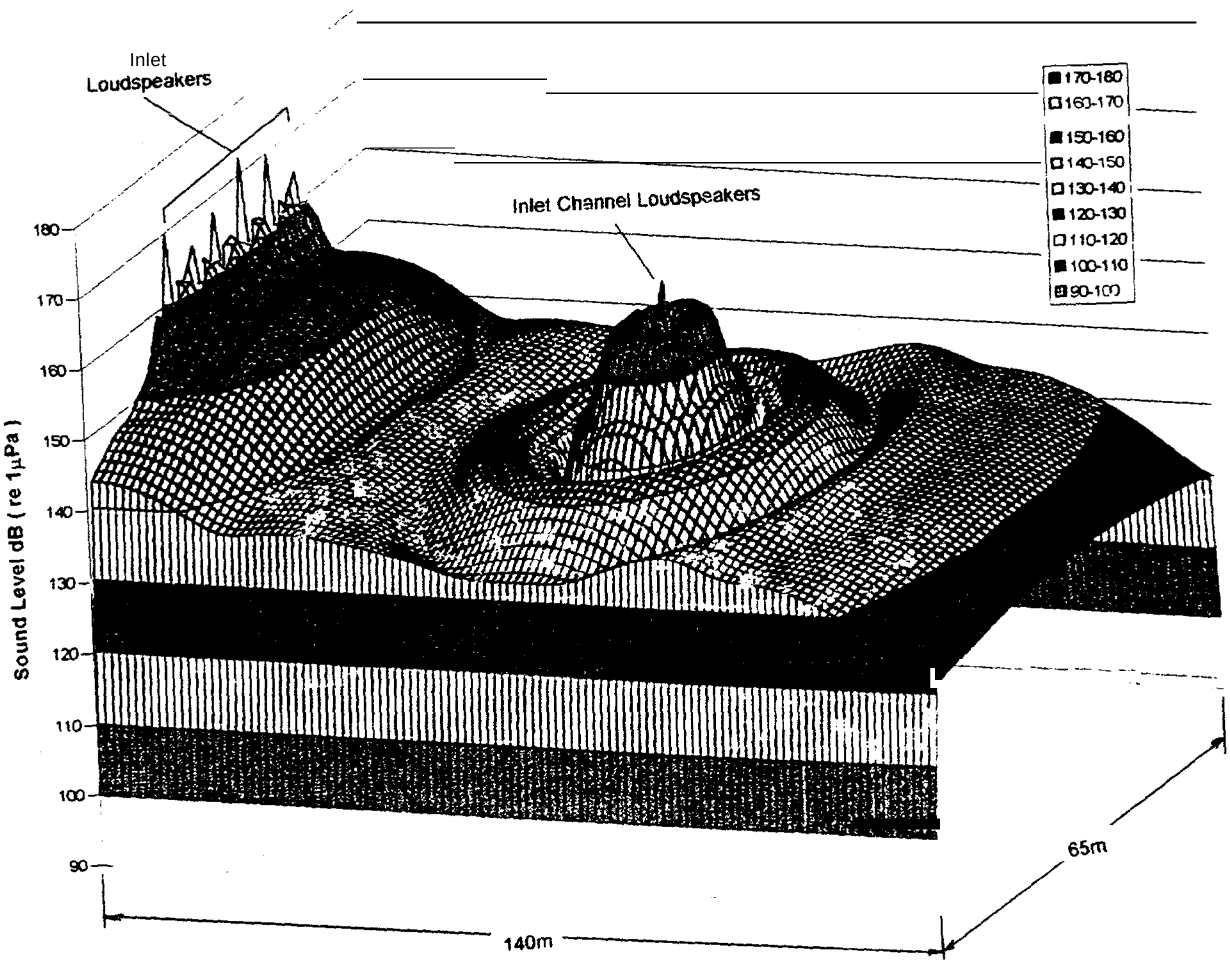


Figure 18

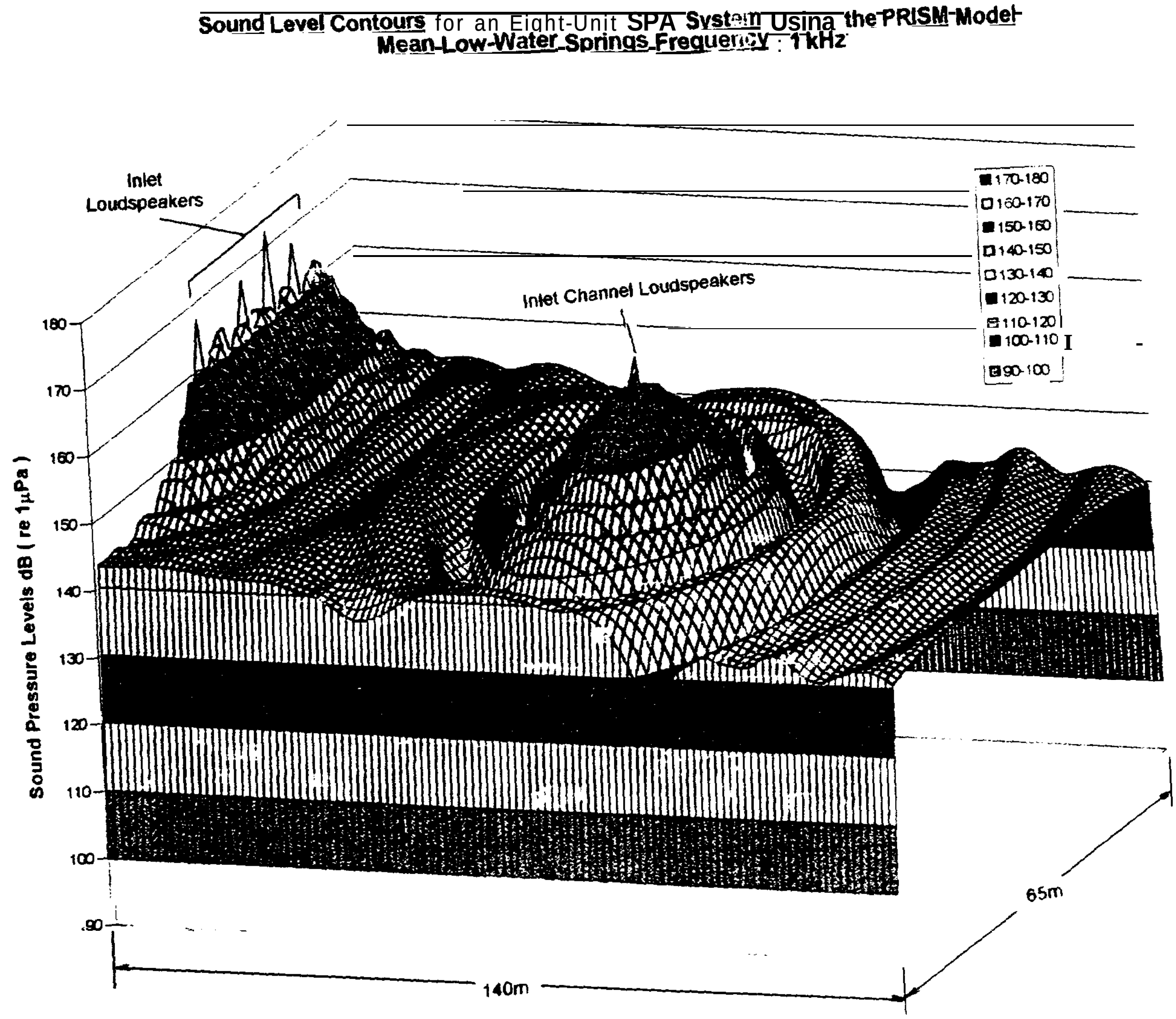

Sound Level Contours for an Eight-Unit SPA System Using the PRISM Model
Mean Low Water Springs Frequency : 1 kHz
Inlet Loudspeakers
Inlet Channel Loudspeakers
170-180
160-170
150-160
140-150
130-140
120-130
110-120
100-110
90-100
Sound Pressure Levels dB (re 1μPa)
180
170
160
150
140
130
120
110
100
90
140m
65m

Figure 19

Sound Level Contours for a Twelve-Unit SPA System Using the PRISM Model

Frequency : 200 Hz

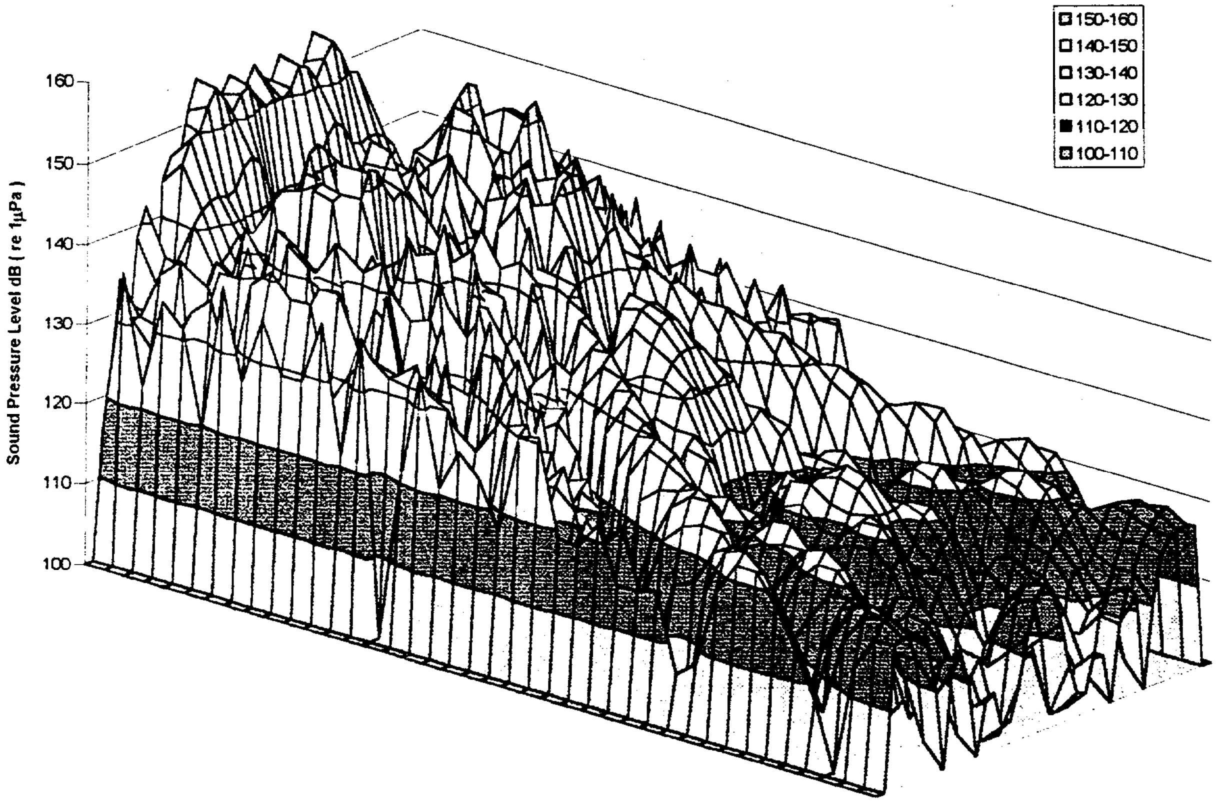


Figure 20

Sound Level Contours for a Two-Unit SPA System Using the PRISM Model
Fresuencv :100 Hz

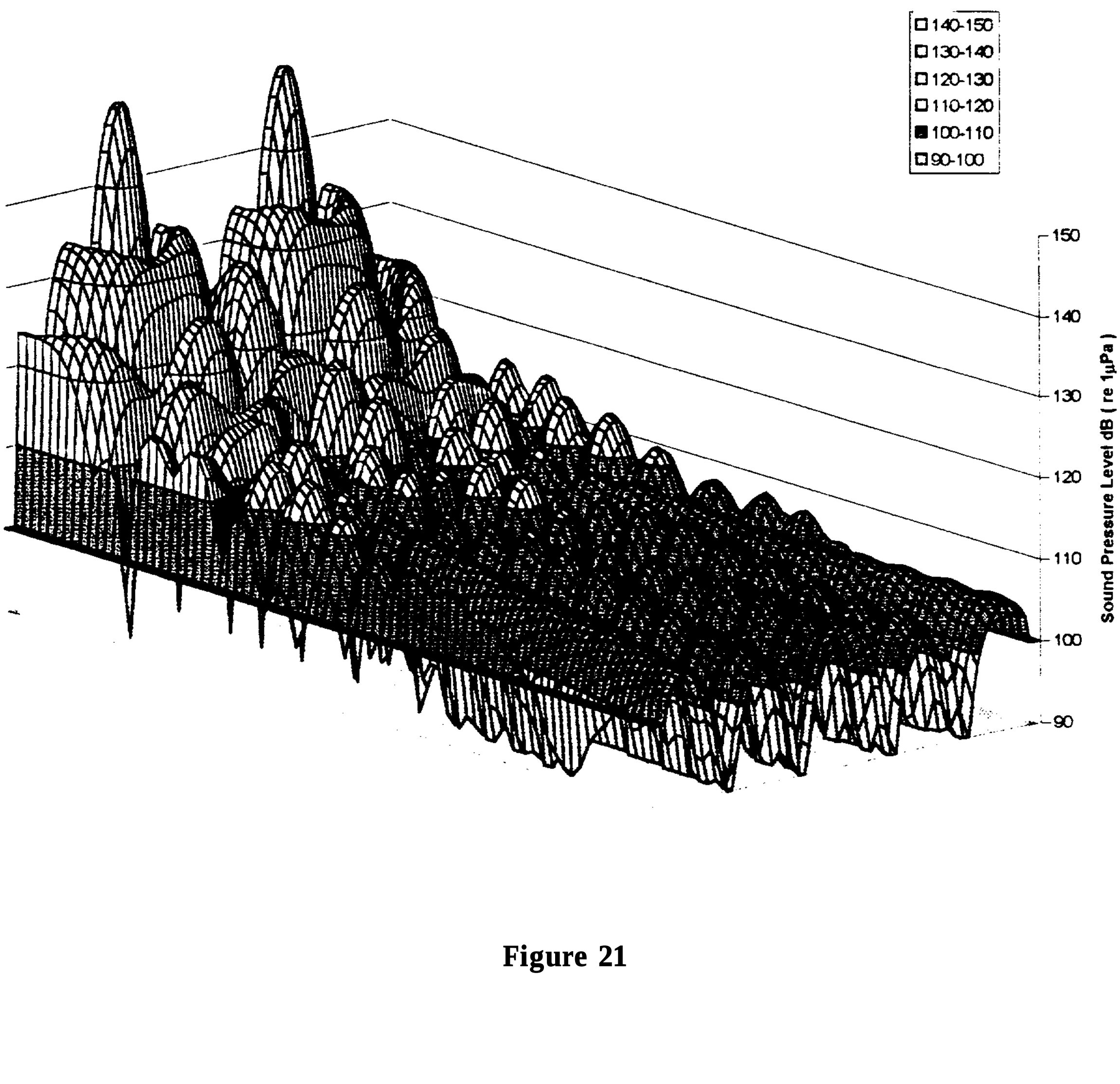


Figure 21

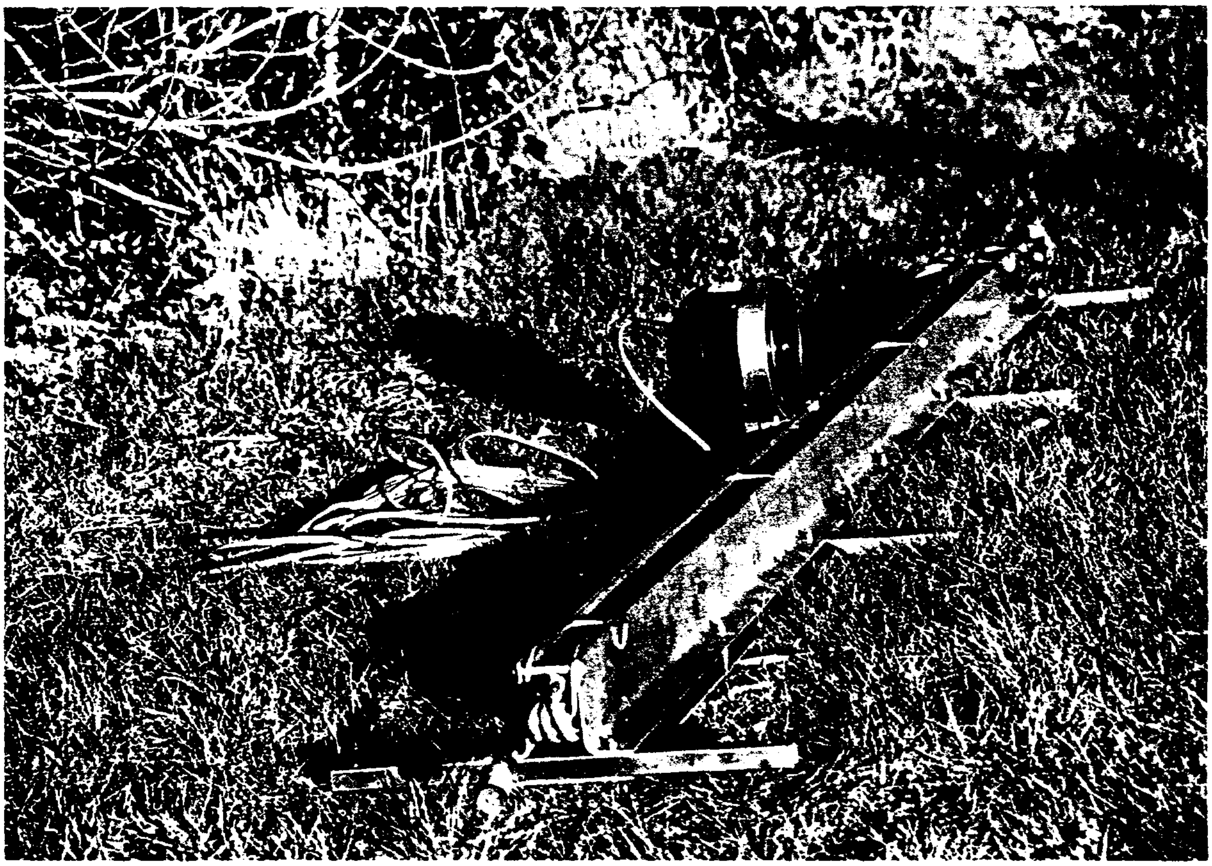


Figure 22

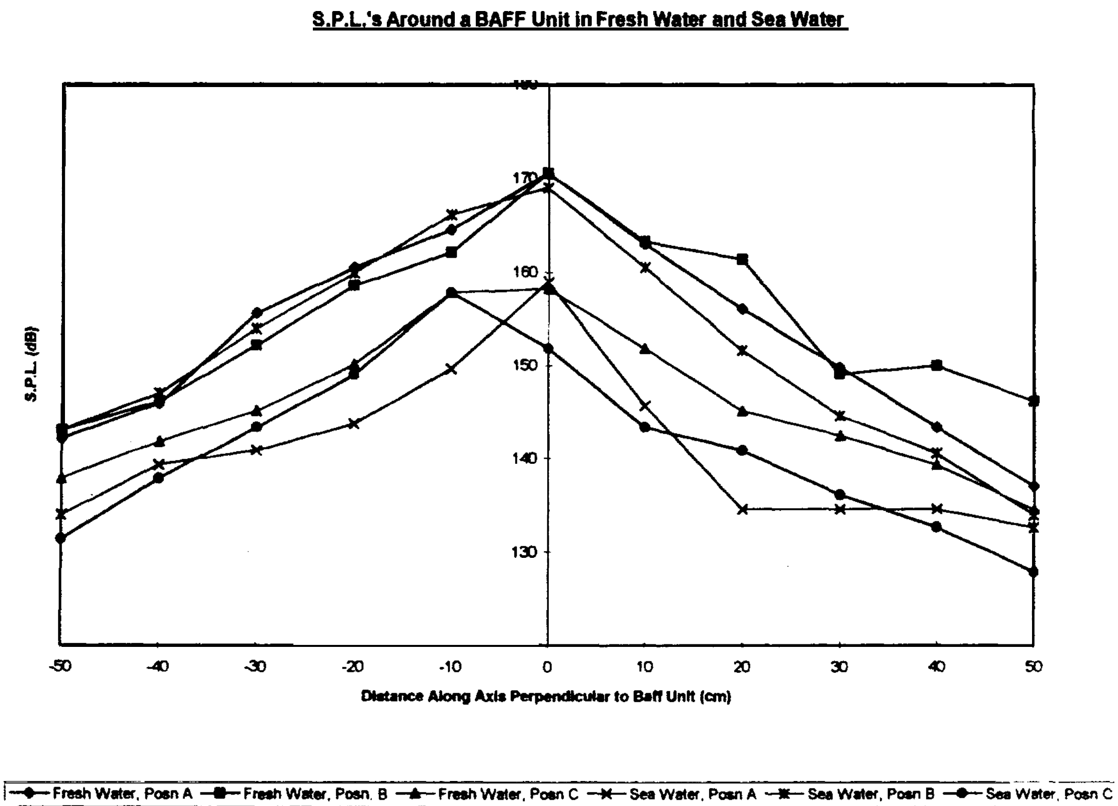


Figure 23

Summary:

Time Domain, Ray Type model (T/R) particularly suitable for this application

May be used as design tool to enable efficient installation and hence use of resources

Also useful for "fine tuning"

Figure 24

DR. TURNPENNY: I shall be as brief as I can. I'm Andy Turnpenny with Fawley Aquatic Research Laboratories. **By** way of background, I spent 15 years as a power industry biologist in Britain, which is how I got into looking at water intakes and problems of fish protection. This particular interest in sound stems from seven or eight years ago when we were looking at the possibility of developing tidal power in Britain and discovered that there were potentially serious consequences for migratory salmonid and shad populations. Given the scale of this sort of scheme – perhaps 200 turbines, each 9 m in diameter – the cost of any kind of mechanical screening device would have been totally prohibitive. And so the government provided funding to look at acoustic methods, and that's where we began.

I'm going to talk to you about the biological side of the equation. I would like to start with a bit of encouragement by saying that we have had considerable success. At the moment in the U.K. we have a test site for the device that Jeremy Nedwell last mentioned, the BioAcoustic Fish Fence (BAFF). We have a scheme operating on a public water-supply intake. We have another scheme on a flood defense pumping station. We have a scheme on a hydroelectric power station in Scotland. We have a scheme on a nuclear power station which Jeremy Nedwell mentioned. We have one on a coal-fired power station in Holland. In 1996 we have plans for additional schemes on two hydro sites in Scotland, one in the French Pyrenees, several irrigation schemes, fish-farm sites in Britain, and we've just completed a design study for introducing acoustic systems into a number of nuclear power station sites in England and Wales.

So let me tell you a little about how we got there. I will start by talking about signals and signal development. I'm a great believer in 'seeing is believing'. Before we'll commit anything to the water on a test site, we want to see fish moved by the signal that we're going to use. We've developed a range of techniques to do this, but we have settled on a rather simple and convenient laboratory technique. 1 was working with Paul Loeffelman in Scotland on a fish farm where we had a 20-m diameter submerged tank and were looking at Atlantic salmon *(Salmo salar)* (Tumpenny et al. 1993). We then reapplied this technique in the laboratory, using a circular tank into which we introduce a sound projector (Figure 1). This particular tank is only -5 m in diameter, with water depth -1 m. A camera is placed over the top, with lights so we can see what's going on. Rather than merely playing a signal to see what happens to the fish, we found a much more sensitive technique in which we spin the water around in the tank with a pump that is turned off before any experimentation to avoid background noise. The fish conveniently align themselves around the tank in streamlines. This is very similar to a technique described by John Blaxter (Blaxter, Gray, & Denton 1981), looking at reactions in clupeids, and it's much more sensitive than looking at fish movements in static water. Initially you see the fish are holding station in the flow; as soon as you apply an effective signal, they lose that station and the shoal breaks up.

In a good situation, we can get various kinds of reactions, ranging from the extreme – a startle whereby the fish leap out of the water – to the more useful whereby fish 'mill around' and move away to the other side of the tank. The signals that wc use are developed through a 'trial and error' process, but initially we searched the literature for audiograms to get the appropriate frequency range. Jeremy Nedwell mentioned that we work in the frequency range of -20 Hz to 500-600 Hz. The signals we develop have a very wide range of characteristics, changing in frequency, in pulse duration, etc. We run a suite of signals past a selection of fish and score the reactions. When we find positive reactions, we then home-in onto the kind of signal that works best and refine it further.

That's the basic approach. Afterwards, we analyze the video pictures and look at where the fish end up in different zones at varying distances from the transducer. We run a trial for 5 min of sound-on followed by a resting period of 1 hour. We repeat this at least 10 times to look at the possibility of habituation. After this, we do a standard statistical comparison of whether the fish are further away from the transducer when the sound is played. That then gives us the confidence to go out into the field with the signal, using one that gives us the highest avoidance score in the laboratory, measured in terms of the mean distance moved. Of course, it in fact bears no relation whatsoever to the distance you might move fish in the field, because they are obviously artificially constrained by the tank.

Jeremy Nedwell mentioned that we spend a lot of time on the planning of these schemes. I want to give you an example of the sorts of things that we do, apart from the acoustics, and how we apply the acoustics. I will describe a trial that we did at Hinkley Point Nuclear Power Station in Somerset, England, with an intake -500 m offshore, in -15-m depth of water (Turnpenny et al. 1996). The basic concept is shown in Figure 2. The fish move along with the tide, in one direction or the other, and get drawn into the intake, at the rate of many tons per year. The aim of the deflection system here was to install sound projectors onto the structure and design a sound field that would repel fish at a certain distance upstream. The basic idea is that the water going into the intake is contained in a ribbon of streamlines which converge onto the intake. If we want to get the fish past the intake, we have to push them out of those streamlines at a point where the fish have a chance to escape. So the aim is to produce an effective signal at a range far enough away to give the fish time to swim sideways into the lateral streamlines.

I haven't time to elaborate on the various fish-movement models we've used to look at swimming speed of fish relative to tidal velocity and so on. This is the actual structure (Figure 3), and one of my colleagues, Kevin Thatcher, is throwing in oranges. To locate the streamlines, we fitted -1000 oranges with iron nails to make them neutrally buoyant. At the intake structure, we had sound projectors fitted onto the legs of the intake, facing the tidal streams. We then were able to monitor what was happening as the fish approached the cooling-water intake screens. There were very large quantities here of sprat *(Sprattus sprattus)* and herring *(Clupea harengus)*, standard stuff to utility biologists.

Often it's useful to look at our failures as well as our successes. I'm afraid Hinkley Point was one of our failures. After 40 days of testing, we managed to increase capture with sound-on: all species by 58%, gadoids by 36%, and a particularly good response (72%) with clupeids. Even though this was the opposite of the desired response, we were encouraged by the fact that they did react to the sound at all. And on that basis, we were funded by the nuclear industry to conduct further trials. We did a fair amount of investigation to find out why this should have happened. Basically, our understanding is this: A common reaction of fish in the sound field is 'to sound', i.e., to dive to the bottom. At Hinkley (Figure 3) we have an intake which opens close to the bottom. Consequently, as the fish approached, they were going down and concentrating themselves in the layer that the intake was abstracting, and so our catches were being increased. Our interpretation of this, based on studies elsewhere, is that had we increased the sound level and repelled them further away, they would have had the opportunity to move sideways.

I will now talk about successful applications of sound. Hartlepool is a nuclear power station that Jeremy Nedwell has described in terms of acoustic planning. We ran trials there the beginning of 1995 by collecting fish from the drum screens during alternating periods with and without the sound system operating (Turnpenny et al. 1995). You have to design these projects carefully to avoid complicating factors like residence of fish between intakes and the screens. In these studies, we spend a lot of time tagging fish and looking at how long it takes them to go through the system. At Hartlepool we had something like 40 species, of which 80% were sprat and herring, the clupeid species. Overall we had a 50% reduction in catch; in the case of herring, a hearing specialist, 79%. Sprat, which qualifies as a hearing specialist, was also strongly reduced by sound (61%). Whiting *(Merlangius merlangus)*, which is like the cod, has a swimbladder but it's probably not very closely connected to the inner ear. Then when we get to fish without swimbladders, the flatfishes, the reduction in catch was down to 15.6%. I must admit, I was surprised that we had any effect whatsoever on the flatfishes, although I should point out that over this period, the result was not statistically significant ($p>0.05$). I won't go into any more detail on that.

I now want to mention our trials on a freshwater system in which we used the linear transducer (the BAFF) that Jeremy Nedwell mentioned. This site (Figure 4) has a small river, the River Frome (Dorset, England), only -12 m across, with an old millrace feeding off it, at the end of which is a counting chamber, with TV cameras and so on, so that fish going down there could be recorded and counted. The barrier was placed across the river to divert fish into the entrance to the millrace. The major aim of this was to do a census of salmon smolts *(Salmo salar)*, but it provided the opportunity to test barrier efficiency as well. A gap was left at the end of the barrier nearest the opposite bank to allow the upstream migrants to go on through. The barrier effectiveness was monitored over the season (Welton et al. 1995).

The study comprised many different trials, too lengthy to report here. But I'll give you one of the results that was obtained fairly quickly. This was achieved by a group of biologists stationing themselves on a bridge over the stream and simply counting fish at the height of the smolt run. It has an annual run of -13,000 smolts, very small by U.S. standards but quite reasonable by British standards. On this particular date of observation, 575 smolts were diverted and 50 went the wrong way, i.e., they passed by the end of the barrier. Interestingly, they also observed a few fish going down the wrong way, so to speak, then turning back and joining the rest of the shoal that was going the right way. The barrier covered only -90% of the river width, so this works out to about a 92% effect. Subsequent results have shown similarly good performance of the BAFF system.

The other factor to mention is an assessment of a sound barrier to determine whether it would disturb the upstream migration of adults. Over the period of monitoring, 22 adult fish passed upstream with the system on, and 23 with it turned off. This was not significantly different ($p<0.05$).

Next I will describe a rather different scheme. This is in the City of York and is located at a flood-relief pumping station (the Foss Barrier) on a river where cyprinid and percid fish live. When the pumps were turned on, many fish were drawn in and killed in the Kaplan pumps and carried out into the river on the other side. The station is owned by the National Rivers Authority, the regulatory authority for fish in England and Wales, and consequently it caused some embarrassment. They asked us to install an acoustic deterrent system, which is now a permanently installation at this pumping station. We have had very high exclusion effectiveness there in controlled trials. With chub, we were able to exclude 87%; with roach, 68%; and overall numbers of fish killed were reduced by 80%.

Basically, I would say that we have been very successful with acoustic deterrents in a wide range of applications. We've dealt with fast upland rivers, slow lowland rivers, chalk streams, estuaries, and marine sites in the U.K. and Europe, and we have found that given proper care and planning, the systems can be very effective. Of course, you also can get it wrong; there are pitfalls. One thing I haven't gone into is the hardware. But as Jeremy Nedwell indicated, the hardware must be designed to meet the particular job. Finally, I think the major factor in our success has been the application of detailed planning on the acoustical field design.

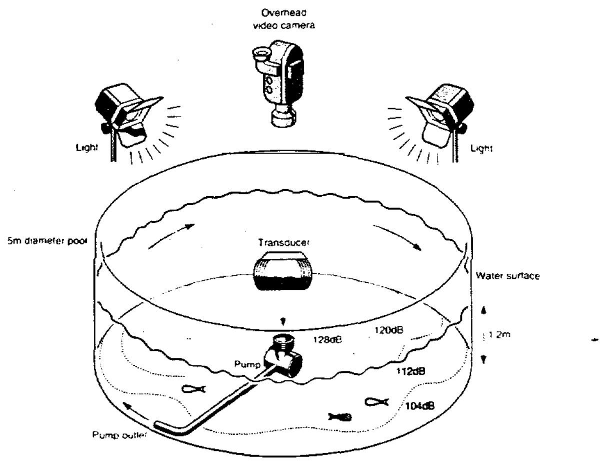


Figure 1
Laboratory test pool.

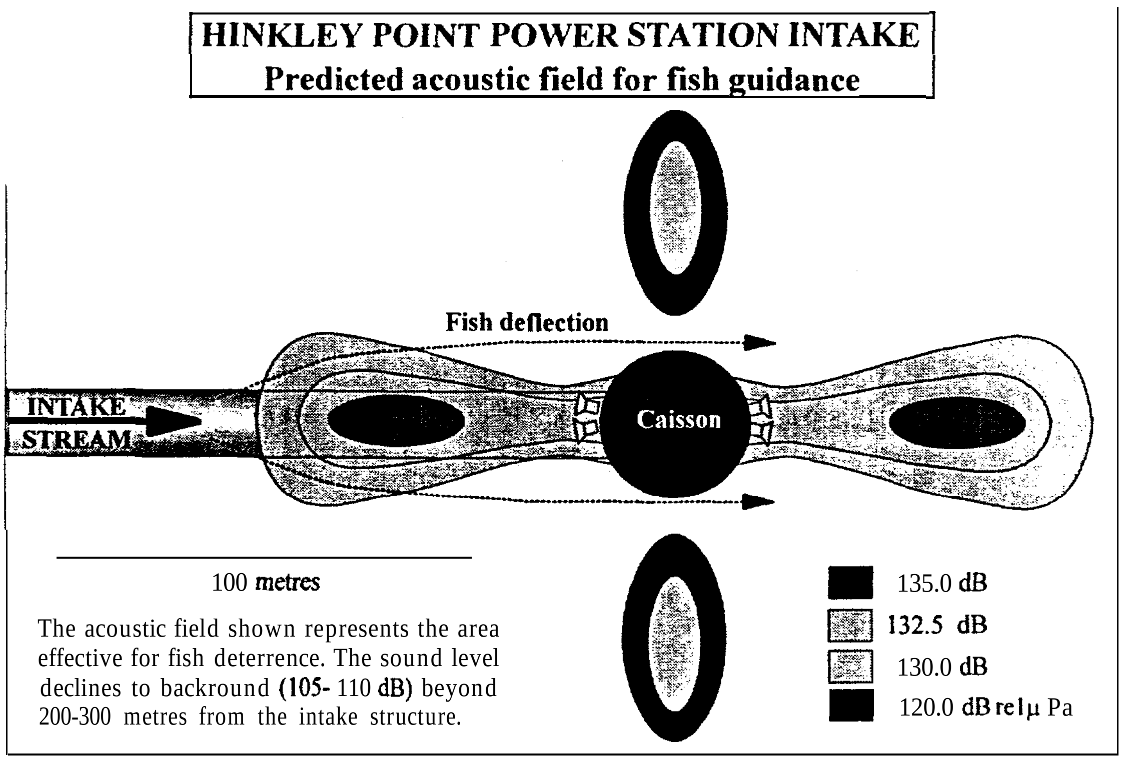


Figure 2
Predicted acoustic field for fish guidance at Hinkley Point Power Station intake.

Figure 3
Locating streamlines using neutrally buoyant oranges
at Hinkley Point Nuclear Power Station, Somerset, England.

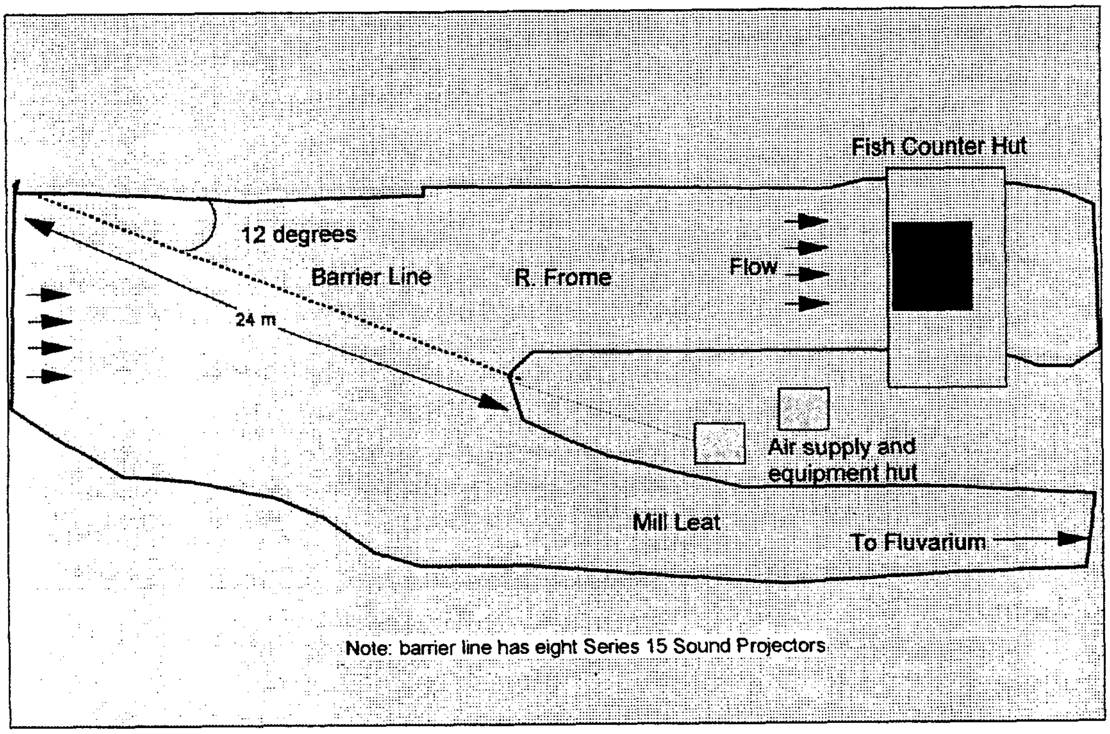


Figure 4
Smolt deflector on the River Frome, Dorset, England.

Question & Answer Session

DR. FAY: I wonder if you would describe some of your signals. I know you used several different ones, but in general, what would you say about them?

DR. TURNPENNY: The general characteristics are that a typical signal contains a number of frequencies in the range of 20-600 Hz. Usually it's important to have the signals continually changing through time -- pure tones are hopeless, in our experience. You can get reactions with pure tones, but they require much, much higher levels. With our signals, depending on species and life stage, we can get different optima. We believe that from the field studies, we're getting effective deflection somewhere between 15 and 20 dB above background, as opposed to perhaps 60 or 80 dB were they continuous signals.

DR. FAY: Are your signals periodic, or would you say they're not noise?

DR. TURNPENNY: No. They are periodic.

DR. CARLSON: A question for Jeremy. I was struck by the sophistication of your acoustic model for more open field, in contrast to the small-tank test environment, given the frequencies that you're using. Could you say something about that? I don't understand how you can learn anything from that tank that would help you very much in the far field, or in the open field.

DR. NEDWELL: Yes. I've tended personally not to look at the biological aspects very much. I look at it mainly from an acoustical point of view. I think what you're saying is, to what extent do we know that measurements taken in the tank translate to the free-field. The answer is, of course, they are very different acoustical media. There is no doubting that. It is a real problem, as I'm sure you're aware, to try to test in a free-field environment. One starts to come into things like anechoic water tanks as a means of testing. We have access to those, but it's not an easy thing to do at all. The approach, as I see it, is effectively what Andy would do in looking at these signals, i.e., a rank order of signals, that some are better, some are worse. And the assumption I think is that rank ordering stays the same in the field. After that, it's mainly a question of taking one of those signals and getting it into the area at as high a level as possible or reasonable. Does that answer your question?

DR. CARLSON: I guess I remain skeptical about using any experiments conducted in an environment that is as acoustically compromising as a tank and translating those out. I guess I will have to learn more about it.

DR. TURNPENNY: Of course, I have read some of the literature concerning the difficulties of acoustics in tanks. And obviously that's a feature that concerned us initially. All **I** can say is that with the transducer set up, one envisions all of these interactions with the water surface and the tank walls, and so on. If you take a hydrophone and connect it to an amplifier and a loud speaker and you track the hydrophone around the tank, then you hear a signal that is incredibly like the signal you hear in deeper water. But because of the lousy propagation conditions in the tank, it dies and you get an incredibly steep gradient across the tank. And when you actually try that out, I think you become more of a believer in the usefulness of the technique. But as I say, the purpose of using the tank is for preliminary screening; and if you can't get a reaction under those conditions, I certainly wouldn't bother to try to signal in the field. If you can get a reaction, then obviously the next stage is to go into the field and evaluate it, away from the problems of the tank. But I think I would vehemently deny any suggestion that it is of no value to conduct these laboratory-stage tests.

MR. MENEZES: Jeremy, one of your viewgraphs seemed to show a plot of the sound at two different points and you could show a time difference of arrival there. The shape you drew had a sharp leading edge and then exponential decay, which to me is indicative of an explosive-type shock wave or really broadband kind of signal. I think I have concluded here that you're using a broadband signal. My second comment has me a little concerned because I thought you were testing frequencies in the range of l-500 Hz. We've tested clupeids using l-500 Hz, and we didn't see anything. We tried ten different ways, varying pulse lengths and sound-pressure levels. And it's interesting you had such good results with the low frequency where we didn't see anything. Looking at your examples, you had a 50-watt signal or a 600-watt signal which converts roughly to a 187–200 dB source level which for l-500 Hz is a pretty powerful source.

DR. NEDWELL: I had better comment on that. That's actually electrical power, if you like. We tend to think 'electrical power' for installations because that's the question you get asked, How much electrical power would you like? The efficiency of the speakers is only 2% or so. So in terms of acoustical watts in the water, we have only 2 or 3 watts. Source levels ran about 170, 175.

DR. MANN: Did you verify your model in the field with arrays?

DR. NEDWELL: The answer is a qualified yes. It's the obvious thing to do, it's what we like to do, and the fine tuning requires us to actually go out and measure, which we do. Verifying a model is a difficult thing. I've been looking at the rivers here, and you would have to be heroic to do it here, because it actually means getting out into small boats in those raging torrents, dropping a hydrophone over the side, and positioning it within a half meter, say. The best sort of verification that we can do is typically one that requires a minimum of points so we can do it most accurately. At Hartlepool, for example, we tracked the hydrophone outwards perpendicularly from the inlet and looked at whether the field we were getting was the same as predicted by the model along its axis. In total I guess we took only 30 measurements, and that took something like 4 hours in a gale with a boat rocking around on the sea, and our staff being rather ill. But under those circumstances, yes, it was good agreement, again, in broad brush features. We got two bumps where the speakers were, not surprisingly. The rate of decay of the sound field was about what was predicted, the levels were typically at the order of 140 dB, so we were reasonably happy with it. There may well be details that don't agree, of course.

DR. MANN: Is your model depth-dependent, too?

DR. NEDWELL: Yes.

DR. MANN: Did you show those?

DR. NEDWELL: Yes. Water depth, source depth, receiver point depth.

DR. MANN: So the figures you showed were just one depth?

DR. NEDWELL: Yes. They were sliced actually at midwater depth. I forgot to mention that I actually brought along a computer-animated model of the field. I will run it during the break for those interested.

DR. NESTLER: Do you know the range of effectiveness of your system? I notice in the tank, you're just looking at a couple of meters. Sheryl Coombs and Mardi Hastings yesterday talked about near-field effects, and I'm sure there's a near-field effect for your transducers. But you are assuming that it's really the propagated wave that's effective. Do you think your system is effective out to 10 m, 100 m, or do you have any idea?

DR. TURNPENNY: I think it depends on what species we are talking about. In the case of the systems for deflecting salmonids, where we are guiding the fish, we work on the principle of a lot of units very close together. Obviously under those conditions, you'll get a nice line of high particle displacement. And in the case of clupeids, for instance, I think rather than talking about range, it's probably more useful to talk about the elevation of the sound pressure above background ambient noise at the key frequencies. And there, as I mentioned, we are looking at 15-20 dB elevation for the best design signals.

DR. NEDWELL: I would like to add a couple more ranges to that. One that we were concerned with for the seals is what I would call the 'range of no possible effect', which is where sound actually drops down to background noise level. And that's well defined. If you measure the noise level, then you can estimate the propagation, you can work out where that would be. In the Hartlepool work, we were very concerned to ensure no environmental effect to the seals. Also, if you have low noise levels, you can get a situation where the sound propagates a very long way. Scottish lochs are particularly bad for that because they have hard substrates, very flat surfaces, and the sound travels well. Under those circumstances, we like to get the projectors up near the surface; we make use of the surface effect to try to constrain the sound field so that sound goes the least-possible distance.

MR. SCHILT: At the power station where you experienced 80% and 60% reduction, that was sort of a polyphyletic group of critters. Was that the same signal for all of those kinds of fish?

DR. TURNPENNY: Yes.

MR. SCHILT: The shotgun kind of --

DR. TURNPENNY: Yes. According to the application for a coastal power station, we tried to develop a broad-spectrum single signal. It may be that we could sharpen that by looking at what is there seasonally and tailoring it to the particular site. But I have to say that in the case of most of our coastal power stations, 80% of the catch is clupeids.

MR. SCHILT: And have you published what those sounds are? We would be interested in knowing what they are.

DR. TURNPENNY: Not yet.

Sonic Fish Deterrence: EPRI/Alden Laboratory's Experience

Ned Taft
Alden Research Laboratory

Dr. Neal Brown
Atlantic Applied Research Corporation
Current affiliation: University of *New* Orleans

MR. TAFT: I'd like to repeat what some of the other speakers have said. I think this workshop is a great idea, and that the people who obviously worked very hard to put it together deserve a lot of credit. I am looking forward to good things happening in the future.

Tom Carlson asked me to cover some of the background of sonic fish-deterrence work that I performed back in the 1980s with the Electric Power Research Institute (EPRI). I will **do** that quickly, mainly to give you a visual image of the types of obstacles that were faced and, in some **cases,** overcome. I would point out that a lot of that work was conducted before researchers in the fish protection field recognized the usefulness of the information base on fish hearing that was available. As a result, much of the early research on sonic deterrence was somewhat trial and error. But I think the work that was performed and the results that were obtained are very useful as we consider future R&D requirements. The information that was developed during the EPRI studies that I will describe is available in various EPRI reports. Chuck Sullivan, who was the Project Manager over the eight years these studies were conducted, is here. If you are interested in getting information on those reports, I'm sure he can supply it.

I'd like to move through the historical information quickly and then get on to the work we did with higher-frequency sounds at the Salem Generating Station for Public Service Electric & Gas Company. I would point out that Mike Haberland of PSE&G (Hancocks Bridge NJ) is also in the audience and will be available to answer questions later, as well.

I first want to give you a visual image of research that has gone on. When we get down to our recent research efforts, which we refer to as infrasound (that is, in the 5-50 Hz range), I will present more detailed data on study design and results. After my presentation, Dr. Neal Brown, our acoustic consultant, will talk about some of the results of our particle-motion generation studies. Dr. Brown was an integral part of our team during the development of the newer sound and infrasound systems I will be describing.

EPRI Studies Table 1 provides a list of all the EPRI studies that have been conducted over the years. Although the species are not noted in the table, the studies encompassed a wide variety including salmonids, non-salmonids, riverine, and anadromous species. Across all of the sites listed, we covered many species. There was a lot of success, particularly with strobe lights. Mercury lights were less successful, although we have seen some species strongly attracted to them.

I would like to quickly cover a couple of the hammer sites listed. The hammer was developed by Ontario Hydro and is commercially produced by FMC Canada (Figure 1). One of the first early studies that we did was in 1987 on the Connecticut River at the Hadley Falls Hydro Project (Figure 2). The dam diverts water into the Holyoke canal system. Holyoke was the first industrial city built in the United States, and it's rather interesting. The water drops successively through three branch canals and provides power to various mills.

What we did here is fairly simple. We were trying to deflect fish to a bypass system that's located at the Boatlock Hydro Station. We put an array of hammers across the first-level branch canal to prevent fish from entering. The hammers operated at a frequency range of -220-250 Hz. Our target species was American shad.

The hammer is basically a 55-gallon drum with a piston inside that is drawn back and released at a regular interval and hits an end plate of a certain thickness and diameter which determines the frequency that is generated. The hammers were lowered into the canal and secured in place with an anchoring system. Hydroacoustic transducers were located at four zones upstream of the hammers to determine the relative abundance of fish as they approached the array. If effective, the abundance of fish should decrease in a downstream direction. Our concept was to look at the relative distance at which we were holding these fish off as they came down. And as with all good studies of this nature, after much planning and implementation, a flood came along and all the fish went over the dam. But looking back on it, I suspect that in the 220-250 Hz range, the shad probably would not have reacted anyway.

We then contracted with Ontario Hydro to test adult alewife, juvenile Atlantic salmon, chinook salmon, and rainbow trout in a semi-anechoic, laboratory tank. It was fairly large, ~10m^2, rectangular, without any flow in it. The hammers were placed in opposite corners of the tank and turned on in sequence: one for 15 minutes, then the other for 15 minutes. Responses were rated by observing the relative distribution of fish over time. Different hammers were tested to produce frequencies in the 204300 Hz range. Very little response was noted with any of the species at any frequency.

We also conducted hammer studies for EPRI at the Ludington pumped storage project on Lake Michigan. The lake is the afterbay of the project, with an artificial upper reservoir. Because of the extensive salmonid stocking program in the lake which we heard about yesterday, with the alewife serving as a major forage species, there was concern that fish were being entrained during pumpback operations and killed. There have been a lot of studies conducted at Ludington over the years that indicate fairly large fish losses. I might point out that the final solution at Ludington, which was just approved, is a 2.5-mile-long net that sits around the intake. The net has been projected to be >90% effective after about 5 years of development.

Our approach to testing behavioral barriers at Ludington was to anchor a boat in the afterbay and mount the test devices from it (Figure 3). Strobe lights, mercury lights, and the hammers were evaluated. We established a "test zone" upstream of the boat and used hydroacoustics to monitor fish abundance with each device operating. A lot of the fish come along the jetties, so the idea was to look at the spatial distribution of the fish and see if we could alter that distribution. With the hammer operating at -32-34 Hz, we found a significant decrease in the abundance of fish in the test area in only one test month. Interestingly, the mercury lights showed a two-fold increase in the abundance of fish, indicating attraction. The strobe lights showed an approximate 50% reduction in fish relative to the control condition. Gillnetting was conducted during testing to permit **species** identification. The predominant fish collected were yellow perch and alewives.

Ongoing research I will now move on to our ongoing research. First, I will talk about what we call 'conventional higher-frequency sound systems' and the work at the Salem Generating Station for PSE&G. Then I will move on to the recent work we've done with infrasound. I have to move through this quickly, but I have papers with me and descriptions of our systems and some of the test protocols.

The Salem plant is located on the Delaware River. The river is tidal at this point, creating relatively high-velocity flows across the cooling-water intake on the ebb and flood tides (Figure 4). The goal of the Salem studies is to determine whether sound can reduce existing impingement of selected key species on the intake-water traveling screens. We started with cage tests to determine basic behavioral responses to a range of signal types, and we plan to conduct tests at the intake using the most promising signals identified in the cage tests. As you've heard lots of people say over the last two days, it's important to understand the environment you are working in, acoustically as well as physically and hydraulically. Therefore, for our initial cage tests, we determined the need to locate our test platform in an environment similar to that existing at the intake structure. We opted to construct a floating test platform which we put right next to the intake. While the ambient sound levels a short distance off the intake were not as high as at the intake, we felt that the location selected was representative of conditions at the intake, particularly with respect to the substrate and wind conditions that influence **sound** propagation and background noise levels. This is a good environment for this because it's tidal and the velocities are very strong, so that if we can get the fish by quickly, they will keep moving on either the ebb or the flow.

Figures 5 and 6 are the plan and section of the test platform showing the test cage in its approximate locations for surface-type tests and for submerged tests, and the different transducer locations. The platform was connected electrically to the shoreline, and a water line was brought out so that we could put filtered water from the shoreline into our test cage. The fish were held onshore and brought out here for testing. The test cage was covered with acoustically transparent plastic. Our sound system and video-observation equipment were-located on deck. We had video cameras located in the cage. The water-tight cage could be totally submerged for testing at lower frequencies in order to get the sound-pressure levels up. We could locate the transducers at various distances from the test cage. Logistically, we ended up putting them in one location and then reducing the sound-pressure levels to simulate moving them further away.

The frequency range achievable with the four transducers was 100 Hz – 145 kHz (Table 2). The computer-driven sound system functioned very well. It's set up so that signals can be put in and played back at random so that the people observing the fish don't know which signals are going in at any point in time. It was impossible not to hear the audible signals because they are so loud, but we tried to make this as blind a test as possible.

Test species included American shad, alewives and herring tested in a mixed group, weakfish, spot, white perch, striped bass, Atlantic croaker and bay anchovy. The fish were collected locally by a contractor, brought over, and held in tanks for a minimum of 12 hours. The testing protocol is summarized in Figure 7. Fish responses were recorded on VCRs, and real-time record were made by us to make sure that we had written notes on every reaction that we saw.

We conducted tests across that 145-kHz range, which we split into 21 half-octave bands. Test parameters are listed in Table 3. For the most part, we exposed the test fish to individual half-octave band widths. In some cases where we observed a positive response, we narrowed down to a tenth-octave band to see if we could get a stronger response in a tighter band. Generally, that didn't work, so what we're going with in the final system to be tested at the intake is a half-octave band width. We did FM chirps, which are like a bird call-a sweep over the half-octave band going from low to high frequency. We also tested pseudo-random noise across the half-octave band, phasing randomly on frequencies within that band. The pulse intervals that we tested were generally 1-sec or 0.5-sec duration, and we tested various combinations of duration. We did other tests with shorter and longer durations, but we have settled on these two durations for the plant's final test system.

The sound-pressure levels tested were maximum (that is, the maximum that we could drive the transducer) and 10 dB and 20 dB below maximum. If we saw a strong response at the maximum level, we then wanted to see, if we dropped down, where that response would go away. We took a lot of measurements, and I picked one as an example. Figure 8 shows the measured output of the Argotec 215 in the last half-octave band width in which it was tested (a 400-566 kHz range with a center frequency of 476 Hz). With the transducer 6 ft from the cage and 7 ft deep, we got some pretty good sound-pressure levels. The cage was at the surface during this particular test. If it had been lower, we would have been -5-10 dB higher than this. And this is at the maximum setting, so these numbers obviously would drop at the -10, -20 dB setting. As you can see, you get a gradient of sound-pressure levels across the cage, and the concept here was to put the fish in, observe their natural behavior without sound for a while, and then see how we could influence that behavior across the wide array of signals to which we were subjecting them.

Figure 9 has a tremendous amount of information in it, and I can't spend a lot of time on it. What we tried to do was give you a visual impression of where fish responded. With the alosids, maximum responses were up around the frequency band centered on 121 kHz. We did get responses, though, down in some of the lower ranges. We got a moderate response out of anchovies over a fairly wide range, centered on 2.7-10.8 kHz. We got a strong response out of Atlantic croaker across a wide range, as well; and these fish were fun because when we hit them with a sound that elicited a response, when the sound went off, the fish would all be croaking away at each other.

We got moderate or weak response with spot and weakfish, with spot responding over a wider frequency range. As in many other studies, striped bass and white perch didn't seem to get very excited about any signal to which we exposed them. We got a weak response over a fair range, but nothing that was dramatic or looked like it would be something that would be effective at the intake. It was this weak response that led to an investigation into the possible use of infrasound for repelling fish. Alden Research Laboratory had been working with Dr. Neal Brown on developing an infrasound system based largely on reading, over a couple of years, much of the information that's been presented here the last two days. We were particularly intrigued with the work that Frank Knudsen presented yesterday. So we went into this with the idea of trying to replicate what Frank and his co-workers had done, and then take off from there to develop an infrasound generator that might be more reliable.

Upon first review, we felt that the limited range achievable with infrasound might be a detriment. But on further thought, we have come to believe that the limited range might be biologically significant. If you're trying to really home fish into a small bypass opening, such as we are trying to do at many hydro projects outside of the Northwest, it's not good to have a lot of sound. You don't want the sound projecting out a long way in a broad pattern, as many higher-frequency systems do. You want a more directed, condensed pattern will have less tendency to project across the very opening through which you are trying to direct fish. So I think we need to get an understanding of infrasound and figure out how to pattern it and set it up in a way that will guide fish without covering large areas.

So we built the same device that Frank Knudsen tested (Figure 10), using the same dimensions and the same stroke, and we tested it in a tank at Alden. Next to this device, we placed two variations of the infrasound generators that Alden and Neal Brown have developed. We had a test facility set-up similar to Salem, with overhead cameras and observers who were standing out of the way, and we went through basically the same test procedure as in the field. We have developed a tremendous amount of information in terms of what frequencies and energy levels we put into the water, some of which Neal will present. We haven't had time to go through the data in depth yet; the volume is somewhat overwhelming.

I haven't described the generators which we have developed because we're filing for a patent and I can't divulge the design at this time. We will show you the frequency spectra and energy outputs that were measured and describe the fish responses that were observed; this is the information that is important.

The test tank was a 16 x 18 x 1.5 ft concrete sump (Figure 11). We placed the three particle-motion generators (PMGs) in the tank for testing. Let me just give you a somewhat subjective evaluation of what we observed and the kind of response we got from the fish. The first species we tested was Atlantic salmon, which was probably unfortunate because they responded in a way I've seldom seen fish respond to any kind of stimulus. It just seemed to drive them nuts, and I have questions about what we might have been doing to their insides that we can perhaps talk about in the panel discussion. But we did get a very strong response. With the piston, we got a similar response to what Frank Knudsen reported yesterday. What we didn't get was a startle response with the piston. But we did see a movement of fish away from the piston, and they would stay away from it. We got some tail flipping, but we didn't get a lot of strong responses like we saw in Frank's video.

With the PMGs that we developed, we saw strong responses for many species up in the 15-30 Hz range. We hadn't really designed these things to be running that high, but they held together. So that's good news. They seem to be reliable. We ran them for many hours, and they held together nicely. With white perch, we got a strong response. I would characterize the response as a 'if the fish had legs, they would have climbed out of the tank' type of thing. Directional, away from the source, and no evidence of acclimation at all. As long as we left it on, the fish were just darting back and forth across the rear of the tank, trying to get away from it. The response was not quite as strong with striped bass, but still somewhat of a strong reaction. The results with perch and bass are good because these are the two species that did not respond to higher-frequency sound in the Salem tests. Weakfish, for which we got a moderate response out of Salem, also showed a moderate response to the PMG in the 3545 Hz range. And spot, which I didn't mention before, were another key species from which we got a moderate response.

Based on the results shown in Figure 9 and the information I have presented on the PMGs, we plan to install a combination of the higher-frequency sound system and the PMGs for evaluation at the Salem cooling water intake. Now I will turn it over to Neal Brown.

	STROBE LIGHT	MERCURY LIGHT	HAMMER/SOUND
Juvenile American shad	Strong avoidance	Possible avoidance	Slight temporary avoidance
Adult American shad	No response	Attraction at night	no data
Largemouth bass	No response	Avoidance	no data
Hybrid bass	Avoidance	No response	no data
Bluegill	Avoidance	Possible attraction	no data
Channel cattish (adult)	Avoidance	Avoidance	no data
Channel catfish (juvenile)	Mild avoidance	Avoidance	no data
Walleye	Strong avoidance	Strong avoidance	no data
Atlantic salmon	Avoidance	No response	No response
Chinook salmon	Avoidance	No response in lab/attraction in field	No response
Rainbow/steelhead	Avoidance	Strong attraction	No response
Coho salmon	Avoidance	No response in lab/attraction in field	no data
Alewife	no data	no data	No response

Table 1

Summary of EPRI light and sound studies to date.

TRANSDUCER	TYPE	FREQUENCY RANGE
Argotec 215	electrodynamic	100 - 566 Hz
G - 34	ceramic stack	566 Hz - 3.2 kHz
F - 56	ceramic sphere	3.2 - 12.8 kHz
F - 33B	ceramic disk	12.8 - 51.2 kHz
F - 33I	ceramic disk	51.2 - 144.8 kHz

Table 2

Transducers used in cage tests at Salem Generating Station.

FREQUENCY

1/2 - octave band width

1/10 - octave band width

WAVEFORM

FM chirp

pseudorandom noise

PULSE INTERVAL

PULSE DURATION

SOUND PRESSURE LEVEL

max, -10 dB, -20 dB

Table 3

Test parameters

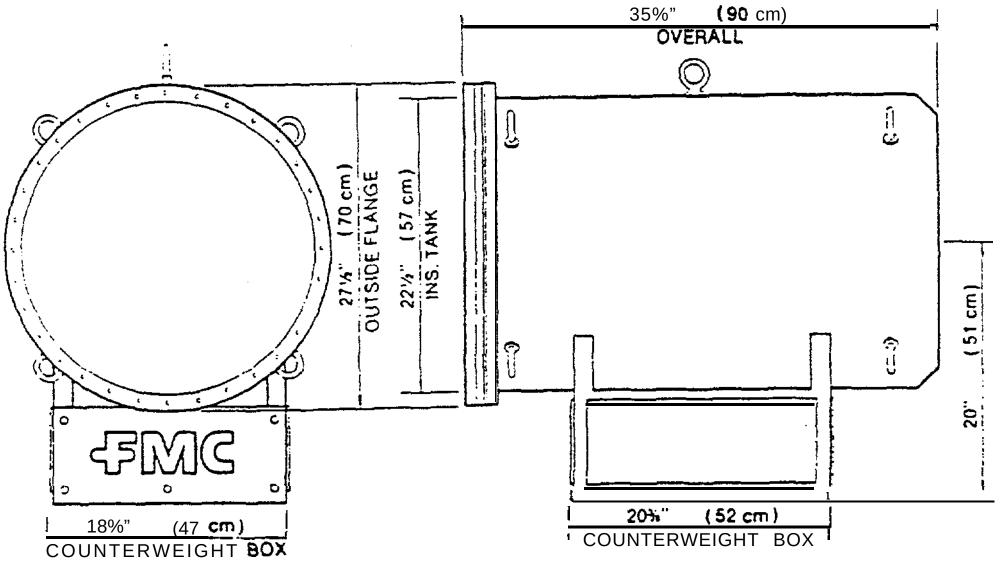


Figure 1

Hammer low-frequency sound source developed by Ontario Hydro and commercially produced by FMC Canada.

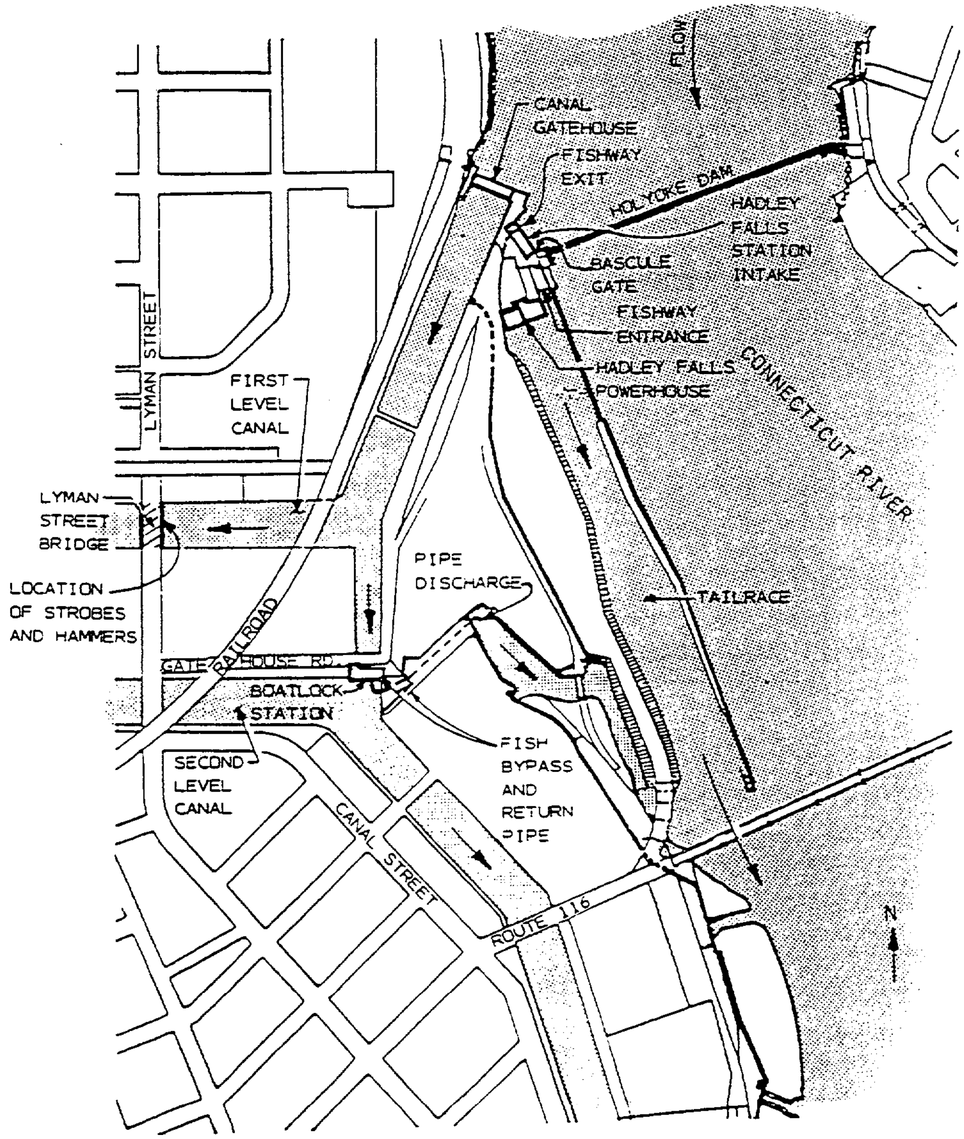
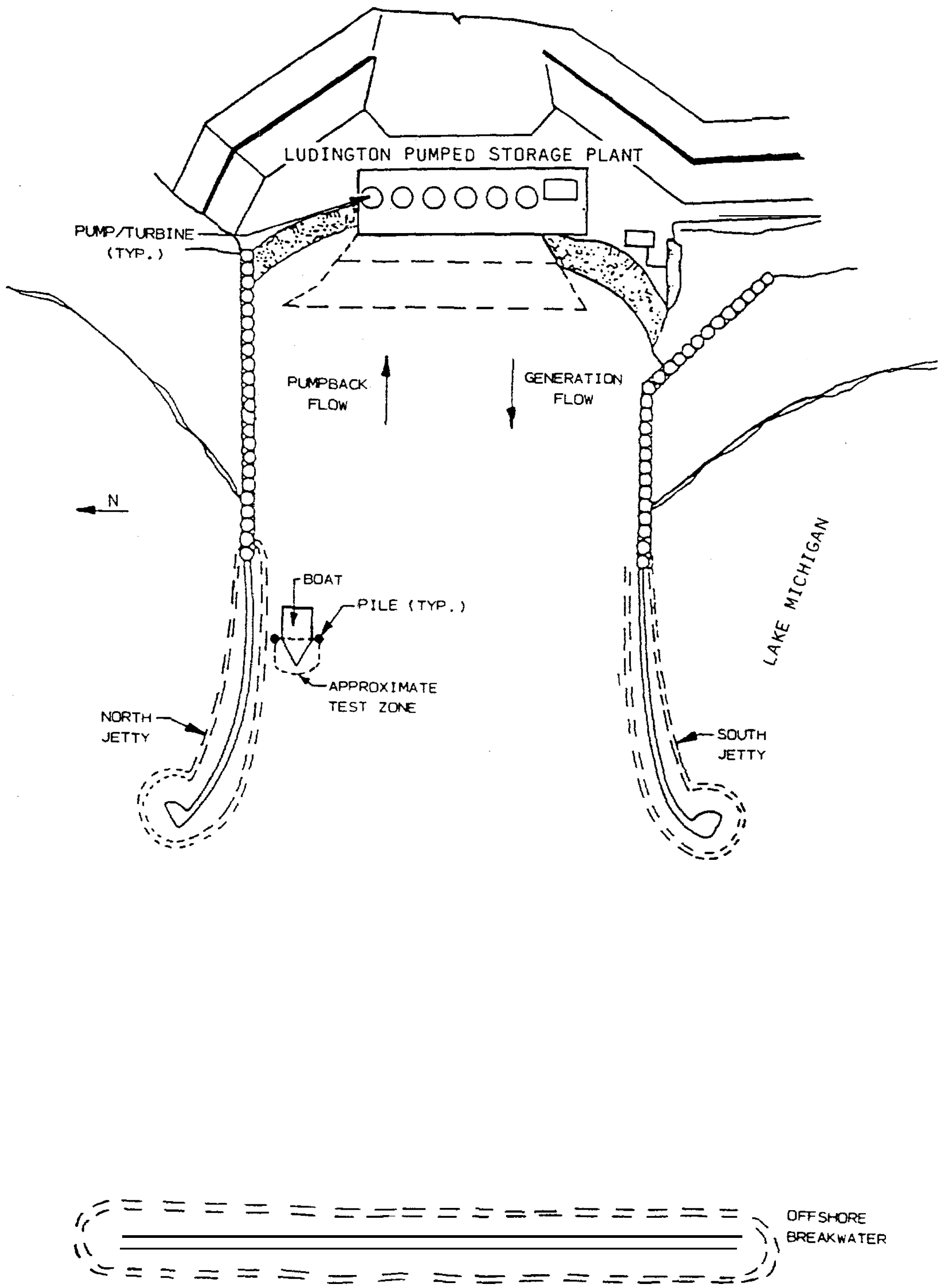


Figure 2

Downstream fish passage facilities and strobe light showing hammer locations at the Hadley Falls Hydroelectric Project (EPRI 1990).



Location of Test Zone, Ludington Pumped Storage Project

Figure 3

Testing behavioral barriers at Ludington Pumped Storage Project, using strobe lights, mercury iights, and hammers.

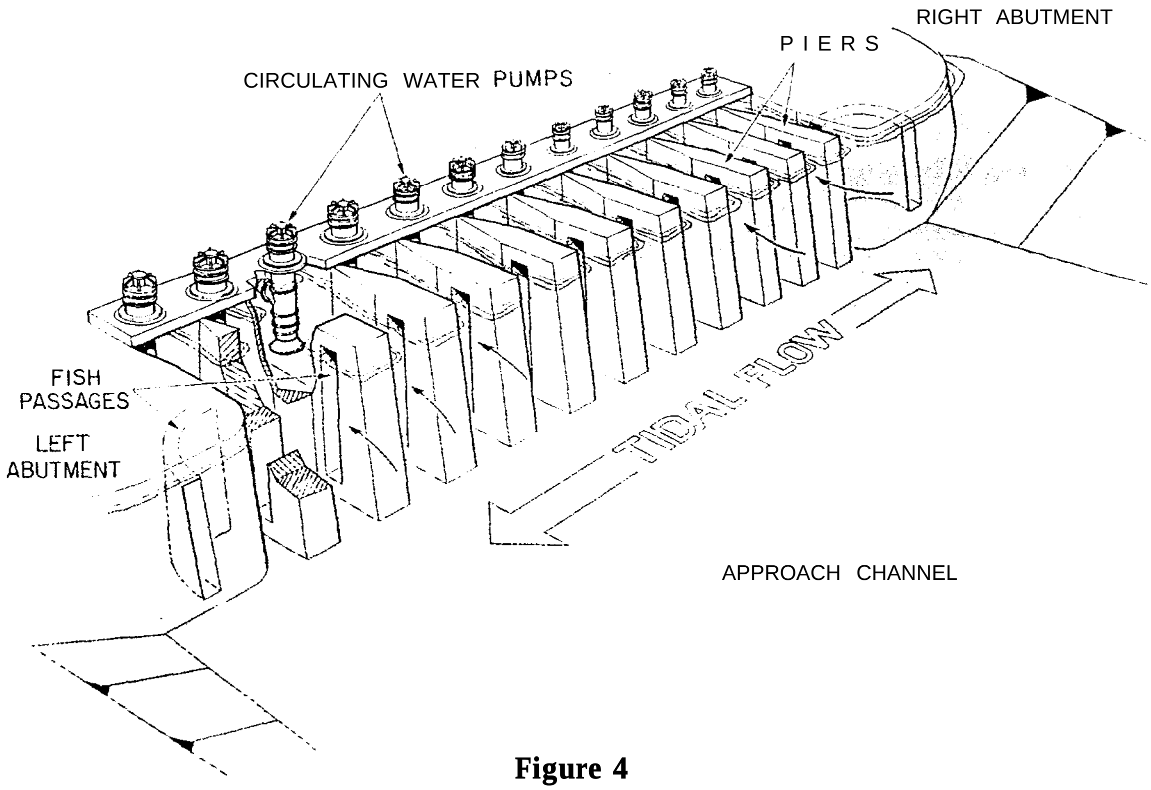


Figure 4

Artist's concept of circulating water pump house at the Salem Generating Station.

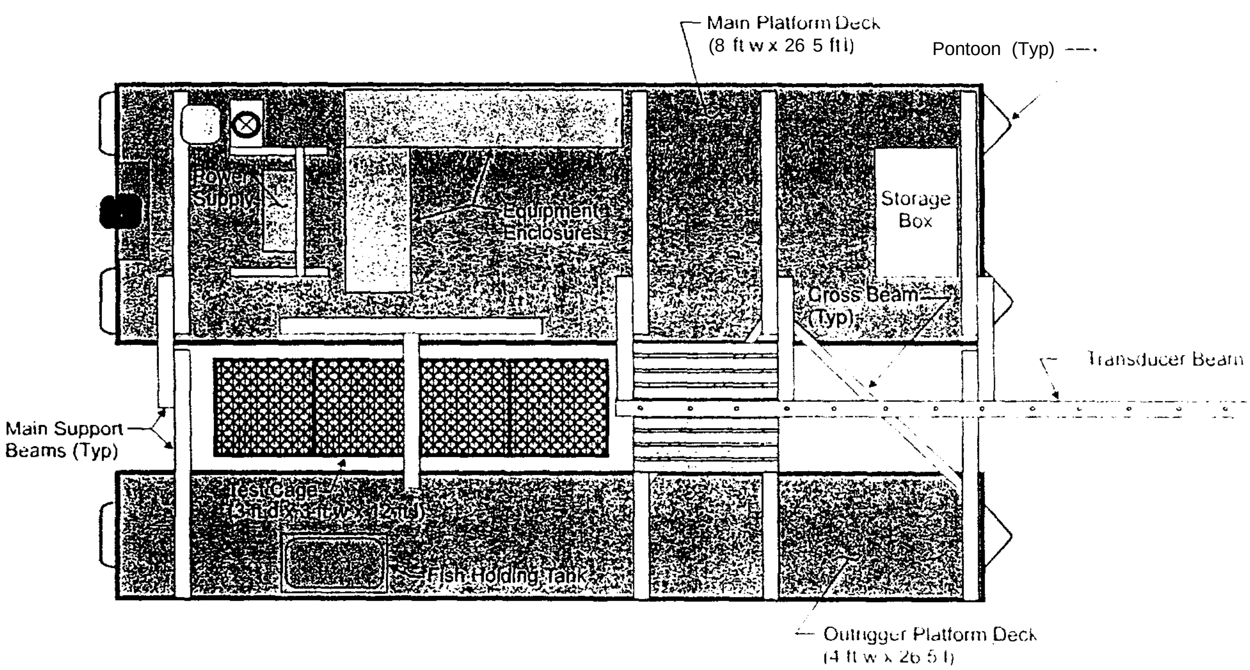


Figure 5

Plan view of test platform for infrasound cage studies at Salem Generating Station.

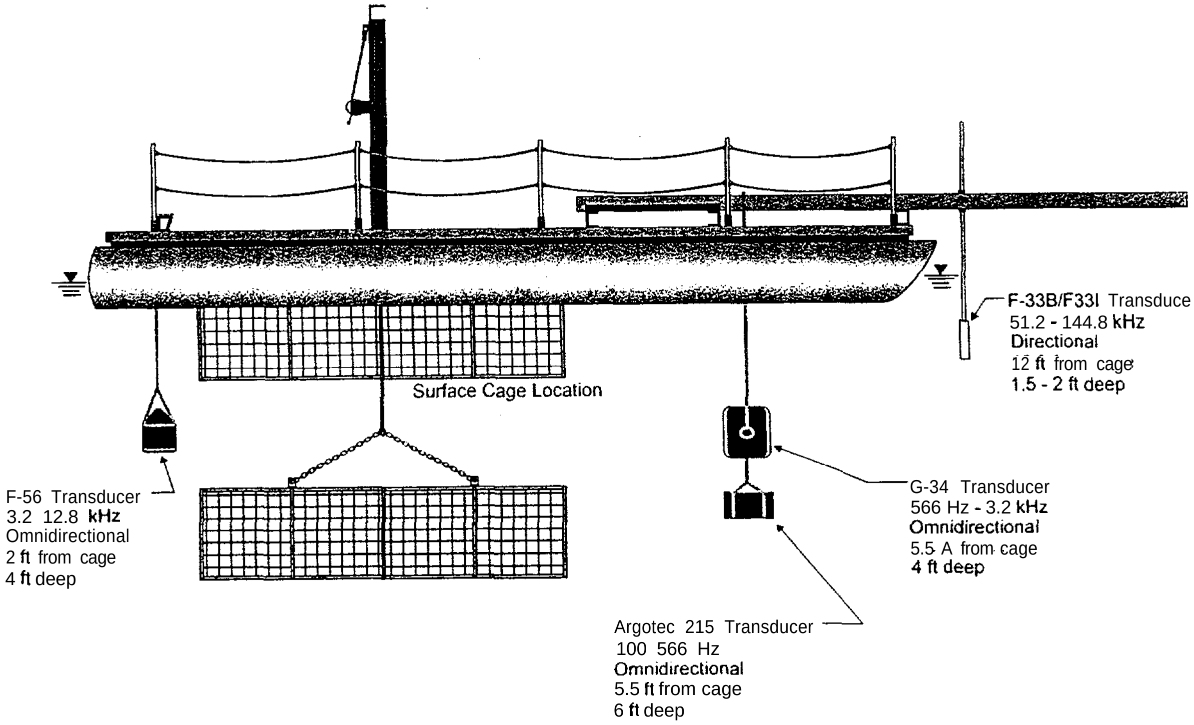


Figure 6

Approximate cage and transducer positions used during cage testing at Salem Generating Station.

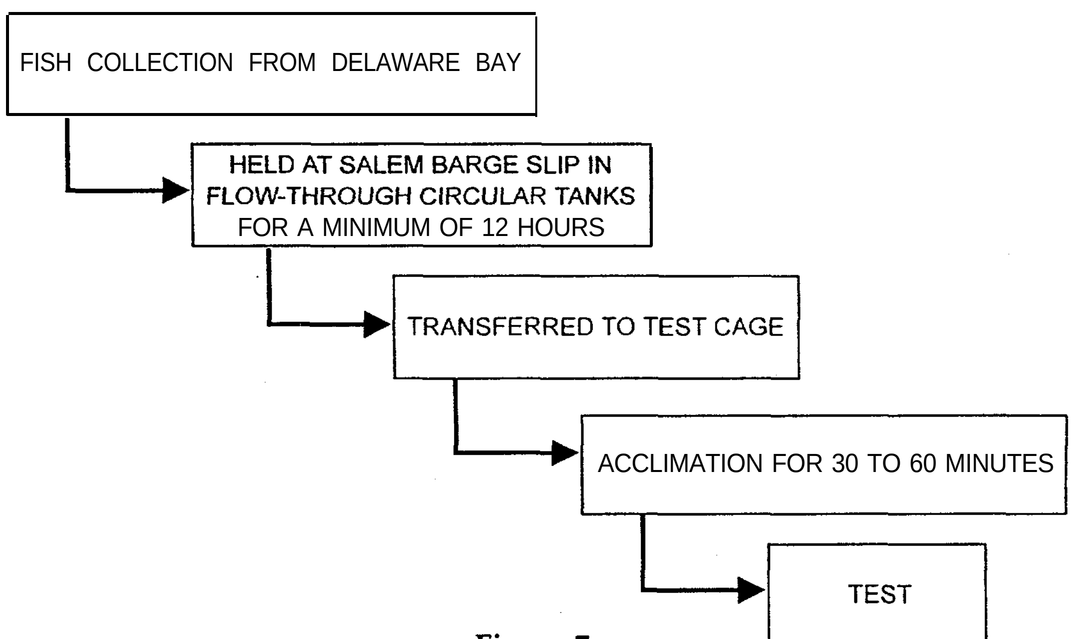


Figure 7

Fish handling protocol for cage tests at Salem Generating Station.

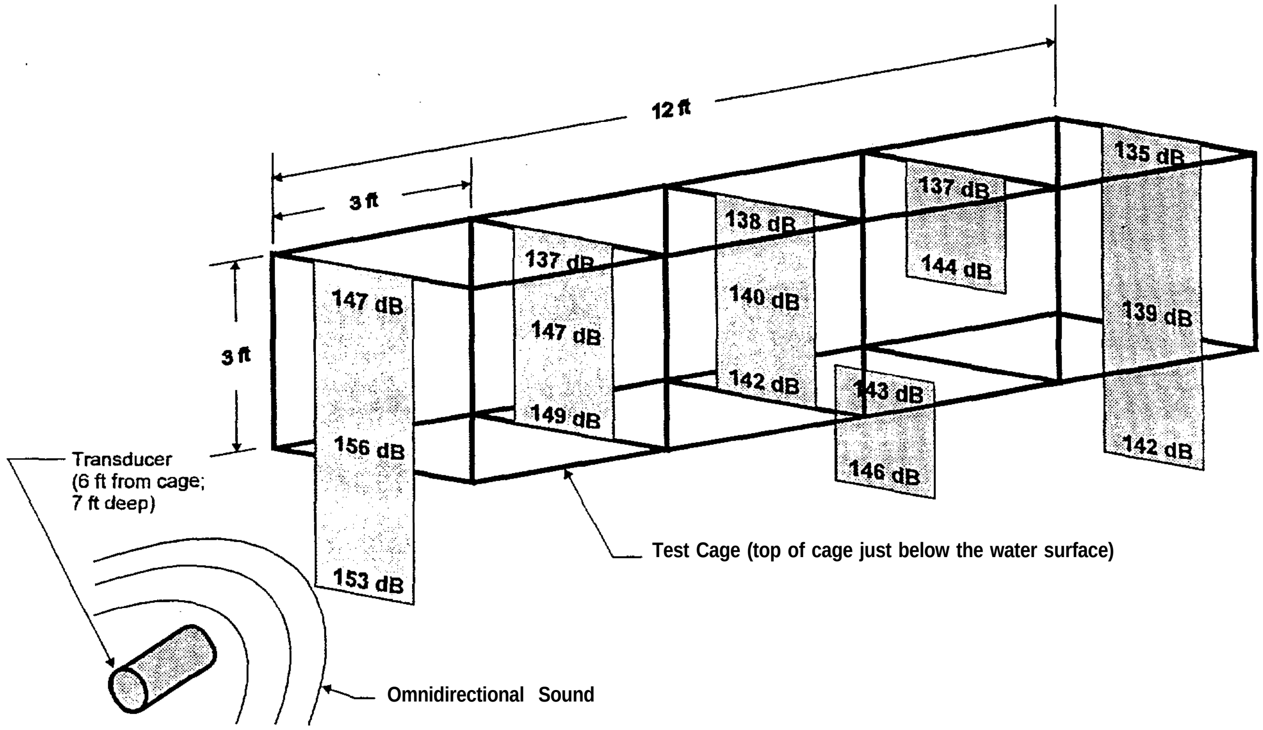


Figure 8

Maximum sound-pressure levels for pseudo-random noise transmitted at a center frequency of 476 Hz and source level 161 dB//µPa@3 ft during cage tests at Salem Generating Station.

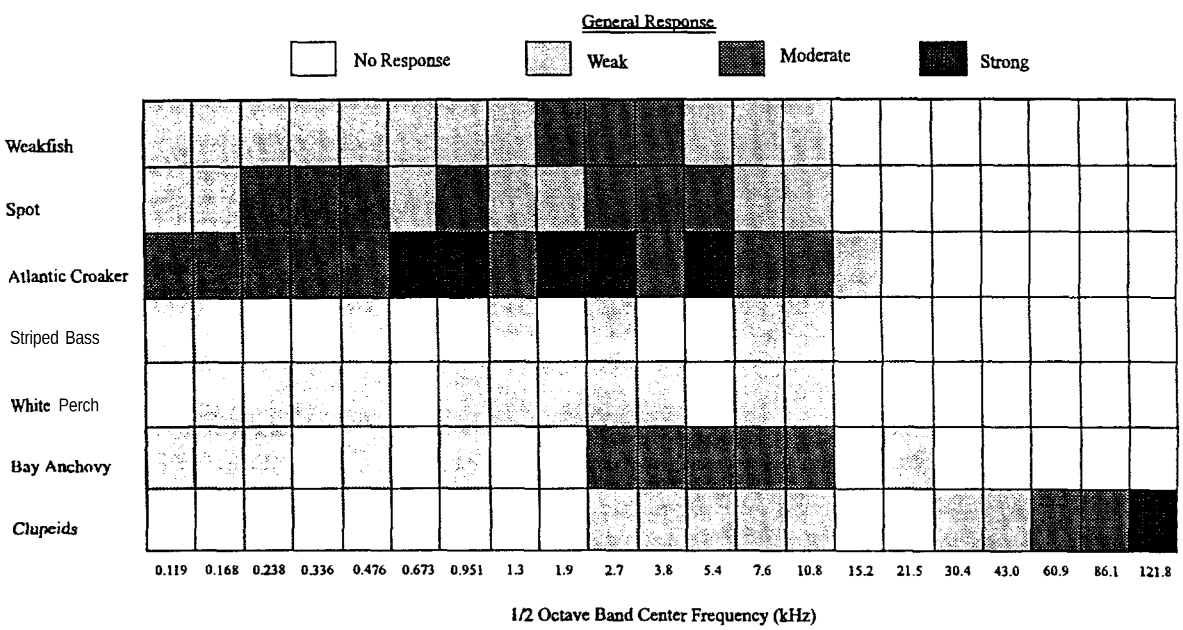


Figure 9

Summary of fish response to FM chirp half-octave bands during cage tests at Salem Generating Station.

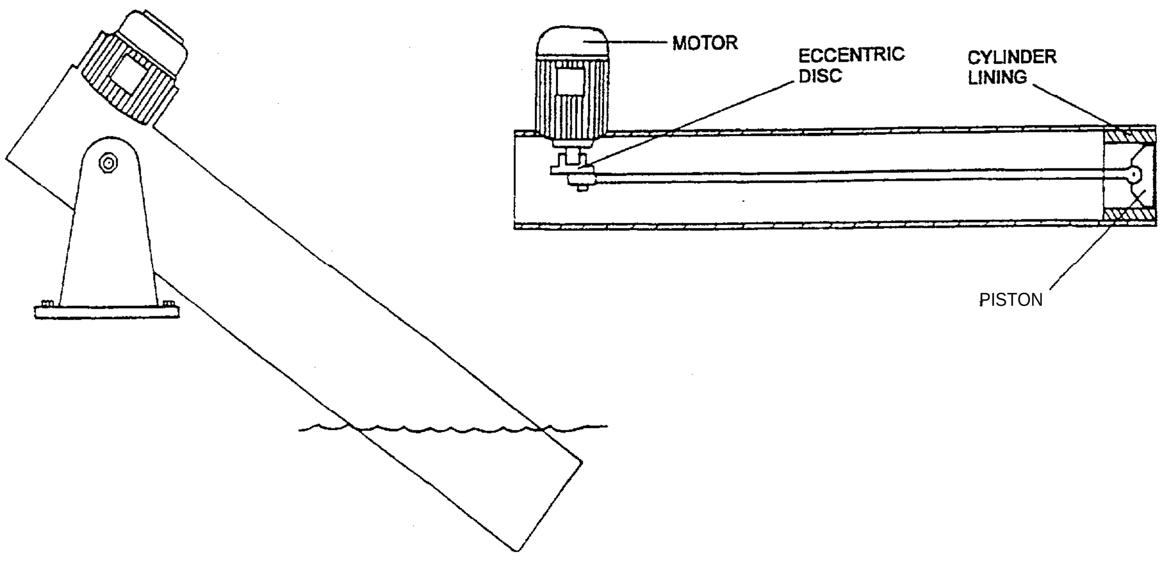


Figure 10

Piston used by Knudsen et al. (19921994) replicated and tested by ARL with infrasound generators developed by ARL and AARC.

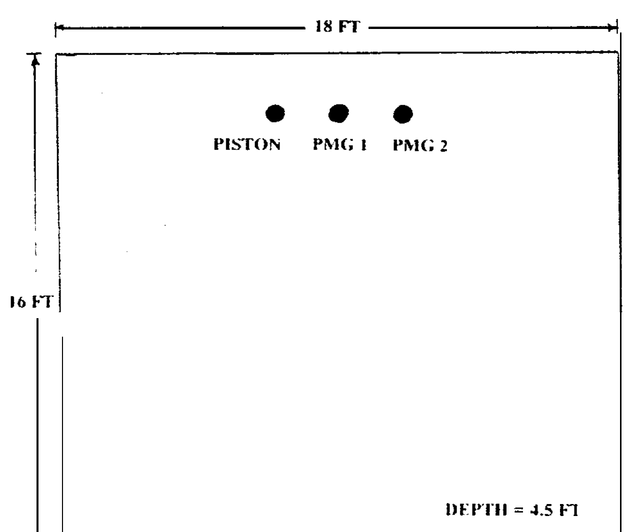


Figure 11

Plan of ARL tank for testing three particle-motion generators (PMGs).

DR. BROWN: This is Frank Knudsen's slide from yesterday (Figure 1) which I have annotated with a few items. Just an observation: Where he was getting his avoidance reaction, and this being awareness, if one draws a straight line here at the appropriate slope, that is equivalent to a line of constant particle velocity, whereas what has been plotted here is acceleration. This happens to be a line of constant velocity. It happens to be –46 dB//1 cm sec^{-1}. But that's not a bad fit, at least on the low end of this thing, and may have some significance.

On the basis of Knudsen's and Sand's results from '92 and '94 (Knudsen et al. 1992, 1994), we deduced that if we could create a particle acceleration in the water in that low-frequency range, in the vicinity of 60 dB//1 μG, we could hopefully deter fish, make them avoid at that level. That was our goal in the 10-Hz range, and we actually designed to specifically reproduce the performance of the piston device that was achieved in Norway. This is the same picture (Figure 2) you saw a minute ago, but I have annotated it with the numbers. With a 4-cm double-amplitude stroke at 10 Hz, i.e., between the extremes, this yields a volume acceleration of 80 cfs^2 . That volume acceleration will vary as the square of the frequency, because this is a constant-volume device, being of fixed displacement. In any event, our design point was 10 Hz at 80 cfs2. Having reproduced the piston device, we put it in the tank at the location we showed you before, and we measured at mid-depth.

These are particle-acceleration levels (Figure 3). Please pardon the abrupt elbowing nature of these curves. It's a matter of fairly sparse sampling in space, and not enough points for MATLAB to give you nice, smooth curves; but in fact you could draw smooth curves through all those little kinks. We found 60 dB out here at a range of almost 10 ft in this tank. Now, the tank is not a "free field," although we found by both calculation and measurement, knowing the volume displacement of this device (assuming it doesn't cavitate) – it's there, that's what you've got (free-field acceleration values) – at a distance of -1 m from the device, and extending out to the vicinity of 2.5 m. The measurement of particle acceleration was almost identical to what you would find in free-field. Beyond that, it became less, and up close it varied, depending considerably on the depth. And beyond ~1 m, it was very insensitive to depth. We have a calculation showing basically that the contours of constant acceleration for a given volume source, at the location we had, were almost invariant with depth, almost vertical lines over most of that range. They get real busy when you get in close, and they get interesting when you get out to the far wall. By the way, these were calculated in exactly the same way that Jeremy Nedwell indicated for sound, except it wasn't sound. As a matter of fact, we were so 'unsound' about all of this, we never measured pressure, just particle acceleration, convinced as we were that that was going to happen.

How do you measure particle acceleration? We invented a little device (which we think others may have used in the past) that we call an accelerometer ball. It is a little sphere (Figure 4), in this case -3.5 inches in diameter. It has three underwater accelerometers in it, at mutually perpendicular orientations, in towards the center of the ball. And it's made slightly buoyant so that it will stay where you put it. There's a little lump of iron on the tank bottom, connected by a string so you can pick it up and move it around, for an anchor. This sphere is attached to the anchor with an elastic band; and when you drop it in the water, you put your ruler down and measure how deep it is. If you don't like it, you haul it out and shorten the elastic and put it down deeper. The elastic, of course, isolates the ball from any vibrations. And the cables are slacked when you set the depth so you don't generate any vibration of the ball by walking around, as you get off the staging, for instance. We also had a net with strings at 2-ft intervals over the water so that we knew where we were, and we coded our location by alphabet and by number.

The system that went along with this is quite simple (Figure 5). We had three accelerometers (Wilcoxon Model 753, I think) connected by long coaxial cables, each of which went into a signal amplifier that provided 20-60 dB of gain, depending on what was needed. And these had a l-Hz high-pass characteristic, so we basically would try to get rid of the very low-frequency stuff to reduce the dynamic range of the signal. These amplified signals went into a multiplexer, which is a sequential sampling device. It's electronic, in this case, and had room for a large number of inputs, though we used only three. It's somewhat akin to a distributor in what used to be the ignition system of an automobile, where you basically close the switch on the first signal for an interval, immediately switch to the second for an interval, and the third for an interval. So you stack the signals from the different accelerometers in time, one behind the other. That stacked signal was then transmitted into a 400-line spectrum analyzer, an HP 3561. And, conveniently, what also comes out of this multiplexer is a trigger signal, like when you start the first sample, so you always get a full story into the HP. Basically, the trigger tells us when to start analyzing or picking up data, so it always picks it up in exactly the same way.

So we have the multiplexer (of course, it was found to be broken when we started, so we had to fix it) and the amplifiers and the spectrum analyzer. Basically, aside from the accelerometer ball, this was all in-house. This is what the piston signal looked like (Figure 6) at this distance, roughly 1 m away, and here are the first, second, and third accelerometers. You can actually see where they switched over from one signal to another. And this is the whole of it. It goes for 2 sec, so basically we have two-thirds of a second of each one. And with a 2-sec sample time, the way the analyzer works, you get a spectrum out to 200 Hz. Now this is linear, and of course the amplitude that you see on this picture depends on the gain we had set-because this is in volts, this is not acceleration. The spectrum that goes along with that is like this (Figure 7). Here is the fundamental frequency we were running, basically at 10 Hz, maybe a little bit off. And there's the line of 10 Hz. This abscissa is from 0 to 200 Hz on a linear scale. The analysis band-width is 0.5 Hz. Again, this is in voltage. By putting in the calibration (sensitivity) of the accelerometers, plus a correction that was made for the fact that we've got three signals – which might be an issue here, a 5-dB issue in there – and the gain that was used on this thing, we find that the peak value at this particular point was 76.3 dB. A dB, here, is a decibel / /1 μG. I also took what I call a 4-Hz band level. I'll show you a picture of that, which includes all the energy in this vicinity, which is, in this case, about 3 dB higher. And this agrees extremely well with what we should be getting out of that device at that position. In these plots, you'll find the data beyond here (140 Hz ?) is probably meaningless, and all of this hatching is a result of convolution, involving some of these peaks with basically the time-sampling characteristics that we were stuck with if we were to do this unshaded. Normally you put a Hanning window on these things to take the sharpness off the end. But if you do that, you lose part of your signal, so we couldn't. It was kind of rough. The band that I'm talking about is between the dotted lines (Figure 8); we try to get all the energy that's in there, because the signal is not that narrow. And for our PMG no. 1, under the same conditions, we have this signal (Figure 9) which shows some disturbances on the upper side, but otherwise it looks a lot like the piston. Its spectrum looks like this (Figure 10); and because of its roughness, it's got some harmonic content to it. But we find, interestingly enough, that even though it is designed to be the same, it is producing – if I adjust for the fact that these things had a different gain – about 6 or 7 dB more on the fundamental out of the PMG than out of the piston for the same conditions, which is fortuitous.

I'll skip over the many spectra that I have here and show what it looks like when you run it at 25 Hz (Figure 11). The level at this point is rather high, our band is up to 96.4 dB//1 μG. Of course, the PMG is adjustable; we can run this thing at various settings, so to speak. And this is the particular setting we used, it tends to go up with the frequency. And the signal is a little cleaner, although it still has a lot of harmonics in it. Now, an overall performance look at this in a fairly conservative manner shows what we get out of it (Figure 12). Again, this is, more or less, pretty close to a l-m position. There is the function of frequency and some of the data points that are on here. There are many, many, many more than this, and they fill in the whole thing; I just took a bunch, one day's test, or something. At various settings we got these various values. And basically a good operating envelope that we have achieved, in fact exceeded on numerous occasions, gives us not quite a straight line, but almost, which is sloped at ~6 dB per octave, as I recall, and that is theoretically correct. We have exceeded this envelope, if you want to push the PMG harder.

Now, how do we apply all of this under the idea of protecting an intake? Again, we're concerned about the PSE&G Salem station in Salem, New Jersey. Here is a prediction using the Knudsen/Sand 80 cfs^2 as a source strength, as it were (Figure 13). And you actually don't need to know the frequency, except that at some point it starts getting to be acoustic. We predict these kinds of contours of particle-acceleration level, and indeed this is relative to 1 μG. The water in front of that intake is 40 ft. deep, and the individual bays are -19 ft wide, to my recollection. So if we center our two units, one at IO-ft submergence and the other at 30, on the center line of a bay and then go out here by 9.5 ft, you come to the edge of the abutment, or the concrete that separates bays. And the center line of the concrete between bays is at 10 ft, so basically this takes you to the center line of adjacent concrete abutments. We get our 60 dB, and since we know that we can generate more than that, we're going to move the 60-dB line further out. Now this pattern is rotationally symmetric about this point (vertical line of PMG centers). This particular calculation assumes these two sources are doing their thing in-phase. If they happen to be out-of-phase, i.e., one negative while the other is positive, the result would look like this, which is not materially different (Figure 13). We still get the 60-dB coverage out to 10 ft. [I'm sorry. In this case (Figure 14), they are in-phase. In the previous one (Figure 13), they were in opposition, acting more or less as a giant dipole.] In this case (Figure 14), they were in-phase with one another, and the fluid comes to rest in the middle because they are both pushing in opposite directions. Bv the way, if vou tried to do this with one unit of this strength, it would probably be inadequate. Here is the calculation (Figure 15) for one unit at mid-depth, and we see that the 60-dB contour doesn't cover enough; in particular, there is lots of room for fishes to sneak in underneath.

A Predator Hypothesis

- Evolution will have equipped juvenile fish with an automatic defense mechanism against predation by larger fish.

- To be effective and timely in dark or turbid waters, the defense mechanism must sense water motion (velocity, acceleration, pressure) independent of sight.

- Since predator and prey may coexist peacefully, at least some of the time, the defense mechanism must be sensitive to a predator strike (rather than mere presence).

- The strike of a predator fish is sudden, with a time scale of fractions of a second.

- The water-motion signal has a spatial scale commensurate with dimensions of the predator, i.e., centimeters to tens of centimeters, or inches to feet.

- The escape reaction must be unambiguous and automatic. The fishlet cannot 'think' about it. Otherwise, he's lunch!

- The prey fish must be able to automatically discriminate a predator strike signal from the 'background noise' of its own motion, motion of its schoolmates, standing flow gradients, turbulence, surface waves, sound.

- The prey fish may lose the defense mechanism when it grows up and becomes a predator in its own right. No longer needed! On the other hand, the predator may need a similar detection and ranging system to find prey in dark or turbid waters. The point is, however, that deterrent testing with adult fish may yield different results and conclusions than with juveniles, which are of interest.

- The space-time description of the predator's strike signal can be presented on a wave number-frequency (k-f) spectral diagram, as in Figure 16. Frequency, f, is inverse time interval; wave number, k, is inverse space interval.

If the typical time interval of a predator strike is in the range of one-half second down to one-sixteenth second, the corresponding frequency range is 2-15 Hz. (To be consistent with wave number, frequency should properly be expressed in radians per second, sometimes known as 'Avis", rather than the usual cycles per second or Hertz.)

If the typical spatial dimension of the water disturbance associated with a strike is from 1 down to 0.1 feet, the corresponding (radian) wave number range is from $\sim 2\pi$ to 20π radians / foot (6-60 feet).

The 'signal' spectrum representing the predator's strike will be found in the common region at the intersection of the above wave number and frequency bands.

If this Predator Hypothesis is valid, a stimulus of prey fish which is characterized by energy in the indicated spectral region should evoke an instantaneous flight response.

• On the same plot, one can indicate the region (in k-f) where plane-wave acoustic energy may exist.

At any selected frequency, the plane-wave acoustic wave number is limited (cannot be larger than) the inverse wave length (x 2π), but it can be as small as zero. Therefore, the plane-wave acoustic region occupies the upper left-hand comer of our diagram (where k is the abscissa and f the ordinate).

In the frequency interval of interest, the plane-wave acoustic region is seen to be distant from the 'predator' region by at least three orders of magnitude in wave number. That is, the acoustic wavelengths are about 1000 times too great to properly represent the spatial nature of the predator's signal.

• Similarly, one can indicate the region(s) where plane-wave hydrodynamic energy may exist. This, like the acoustic limits, depends on the propagation speed of the k-waves.

Because the propagation speed of hydrodynamic waves is equal to the flow speed, for which 1 and 3 fps are shown, the wave numbers for a given frequency are much higher than for acoustics. The ratio is about 5000:1 and 1700:1, respectively, relative to acoustic wave numbers (inverse of the Mach number). The hydrodynamic region occupies the upper-left three-quarters of our diagrm and includes the acoustic region. (If the flow Mach number were 1, the hydrodynamic region would shrink to coincide with the acoustic region.)

In the frequency interval of interest, the plane-wave hydrodynamics region is seen to extend right into the 'predator' region. That is, the shortest hydrodynamic waves (highest k's) very well represent the spatial scale of the predator's signal.

As the predator's strike generates very little, if any, 'sound', but considerable incompressible fluid motion, it is not surprising that a prey fish would be specialized to detect and react to the latter rather than the former. However, this is more properly an issue of signal-to-noise ratio rather than of signal strength alone.

• Prey fish of interest are well suited to express an effective sensor system for the purpose.

That sensor system probably makes use of the lateral line as a linear array of transducers (as shown to be likely by Sheryl Coombs), in conjunction with the ears, acting as whole-body accelerometers (which Olav Sand has shown to be marvelously sensitive).

The length of the lateral-line array is approximately that of the fishlet, which is adequate to yield directional information and signal-to-noise ratio gain for the predator's (higher) wave number signals. That is, the product 'wave number-x-length' is adequately large for a typical prey fish and predator.

This is clear in Figure 17 where the estimated pressure field is shown before a predator fish advancing at constant velocity. The predator, shown in plan view at the upper left, advances from left to right. The prey fish may be found in the rectangular field of the plot and its mirror-image above the predator's centerline. All dimensions are normalized to the predator's body radius so that here a prey fish might have a length of perhaps 1 to 2. This example does not mean to imply that the prey fish are sensitive to pressure or that predators strike at constant velocity, neither of which are adequate descriptors, but the scale of a hydrodynamic 'signal' is illustrated.

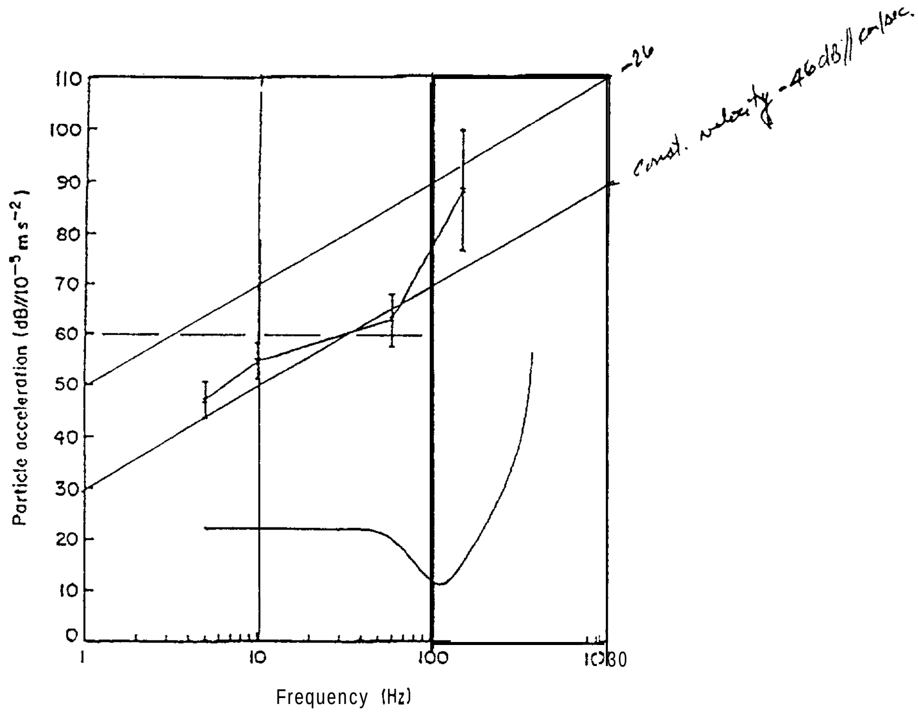


Figure 1
Spontaneous awareness reaction thresholds for juvenile Atlantic salmon (from Knudsen et al. 1992).

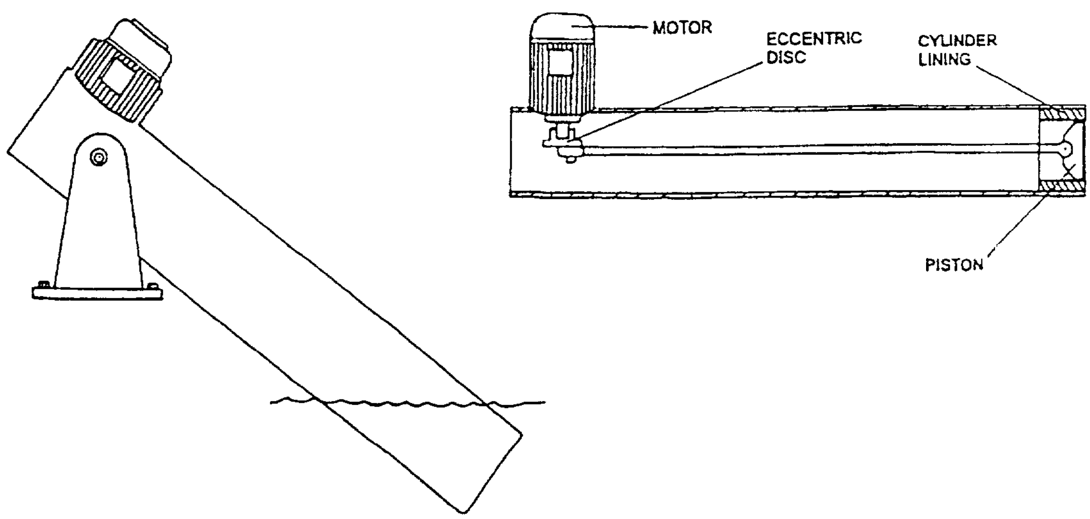


Figure 2
Piston device used by Knudsen et al. (1992, 1994).
With 4-cm stroke (da), yields 80 ft^3/sec^2 (sa) at 10 Hz.

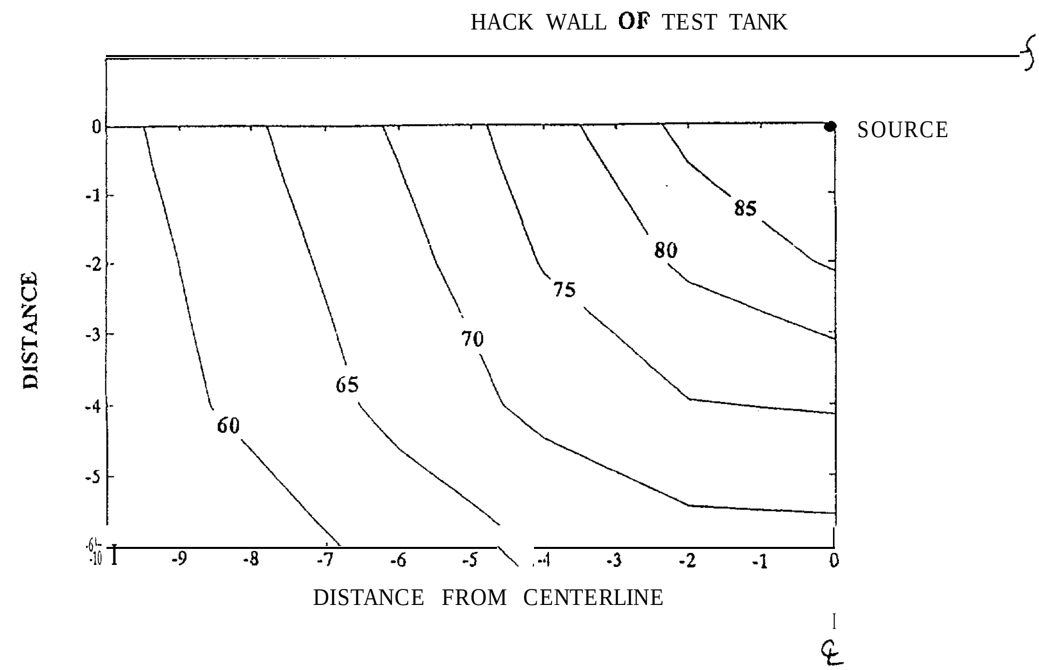


Figure 3
Plan view of particle acceleration levels (dB//μg).
Piston 10 Hz

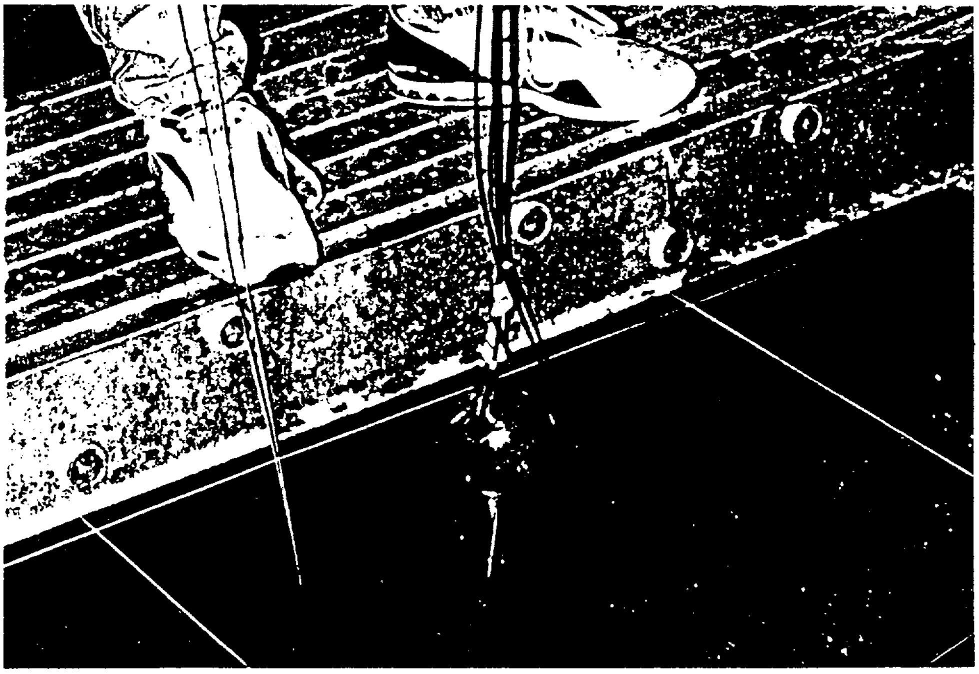


Figure 4
'Accelerometer ball' particle-motion sensor.

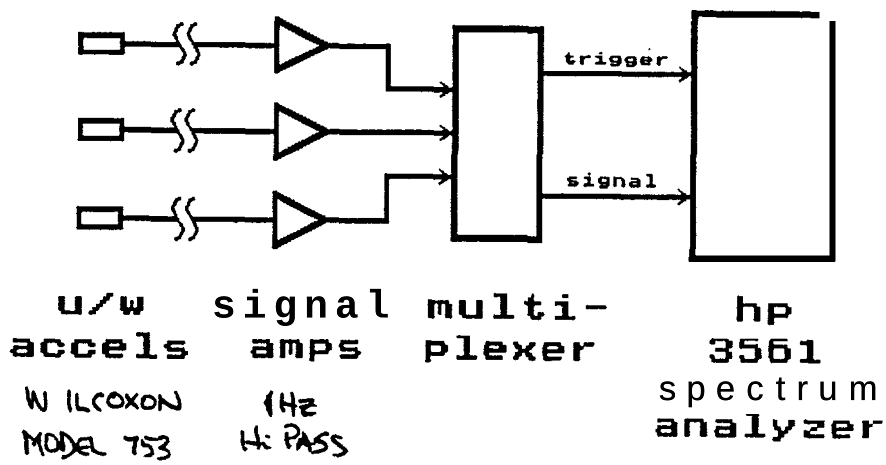


Figure 5
Particle-motion sensor system.

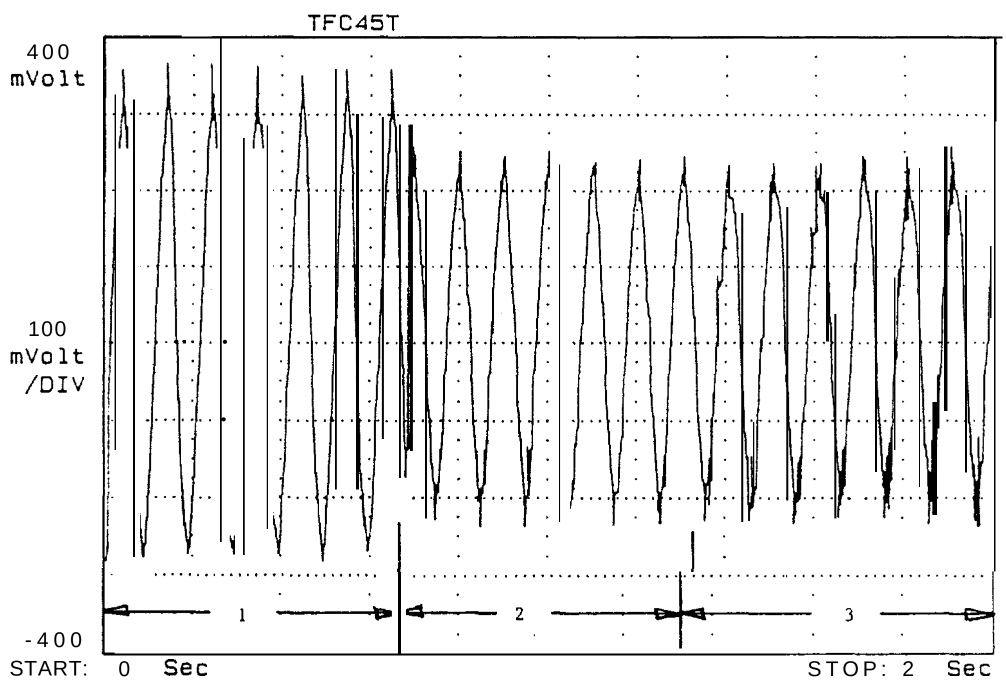


Figure 6
Wave form, three directions. Piston 10 Hz.
Acceleration at location C45.

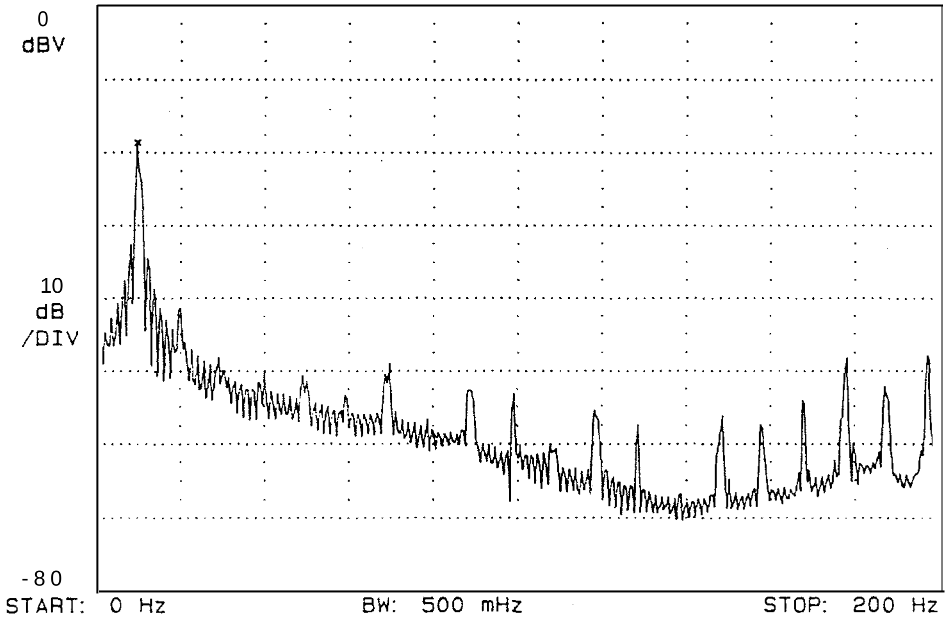


Figure 7
Frequency spectrum, piston 10 Hz. Acceleration at location C45.
Fundamental peak level: 76.3 adB; 4 Hz. Band: 79.3 adB. Gain: 50 dB.

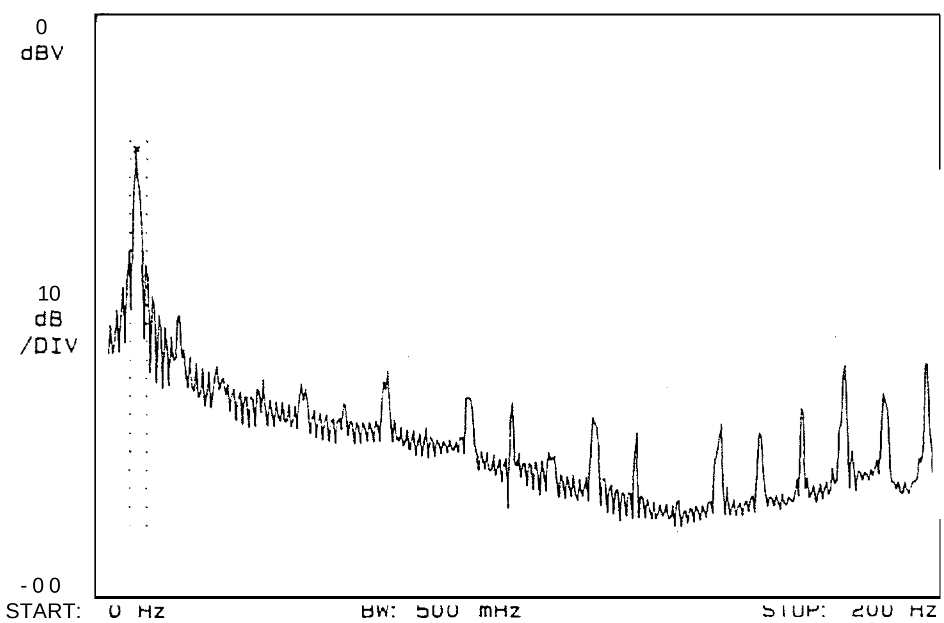


Figure 8
Frequency spectrum, piston 10 Hz. Acceleration at location C45.
Fundamental peak level: 76.3 adB; 4 Hz. Band: 79.3 adB. Gain: 50 db.

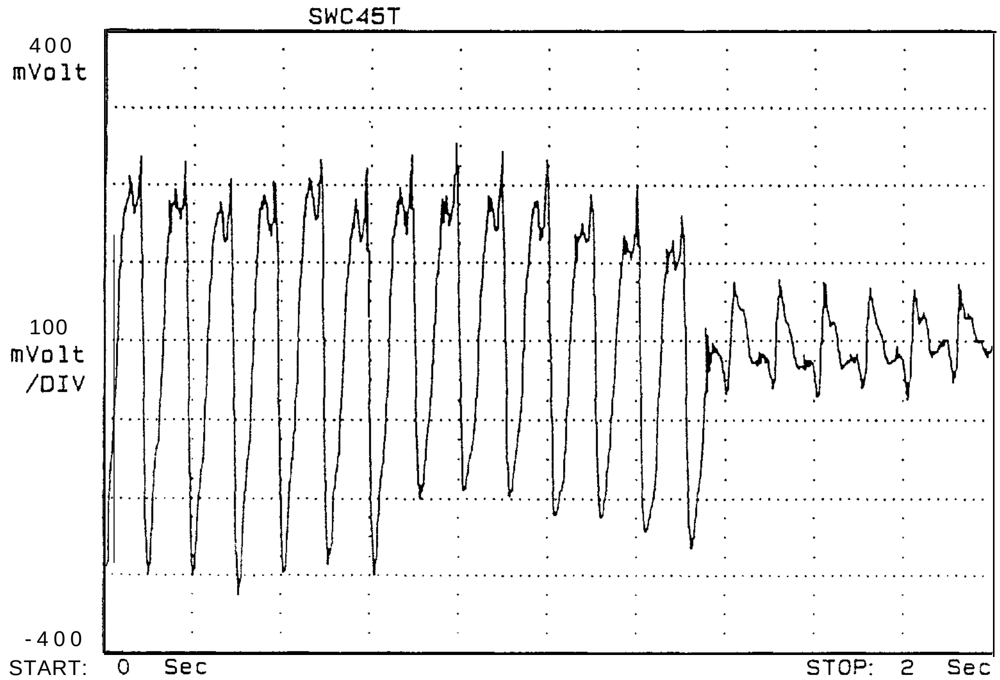


Figure 9
Wave form, three directions. PMG 10 Hz. Acceleration at location C45.

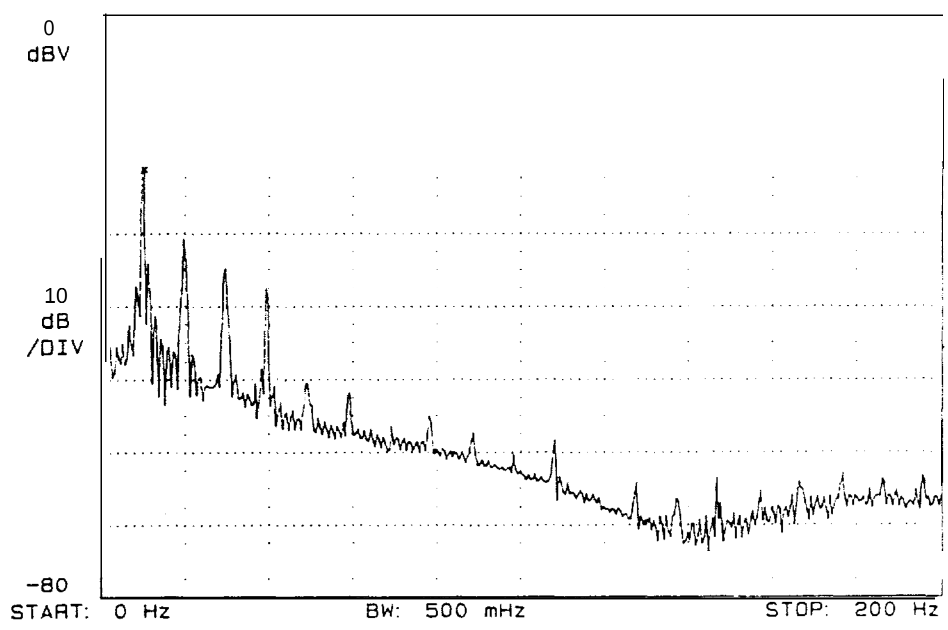


Figure 10
Frequency spectrum, PMG 10 Hz. Acceleration at location C45.
Fundamental peak level: 83.6 adB;

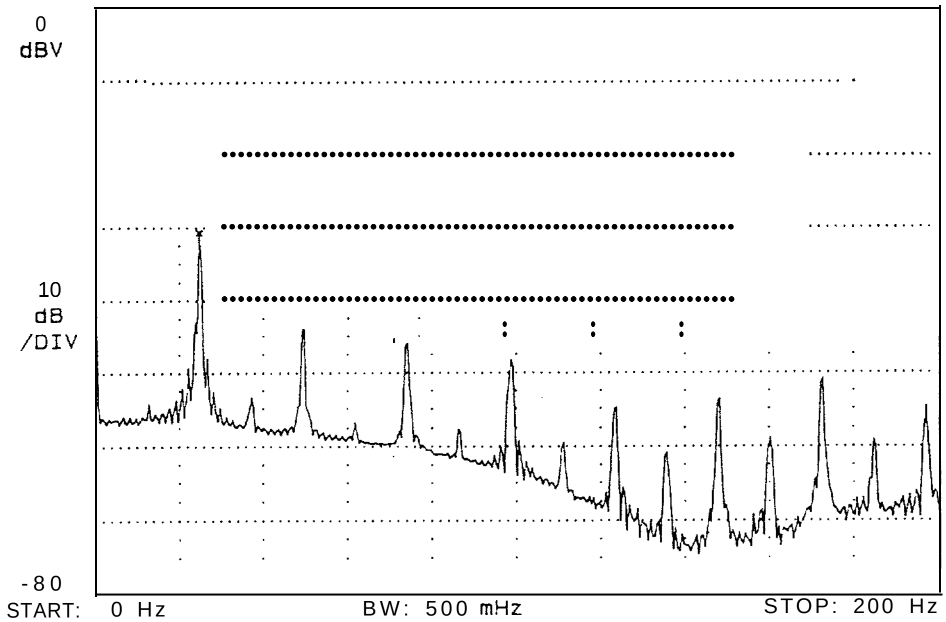


Figure 11
Frequency spectrum, **PMG 25** Hz. Acceleration at location C45.
Fundamental peak level: 94.3 adB; 4 Hz. Band: 96.4 adB. Gain: 20 dB.

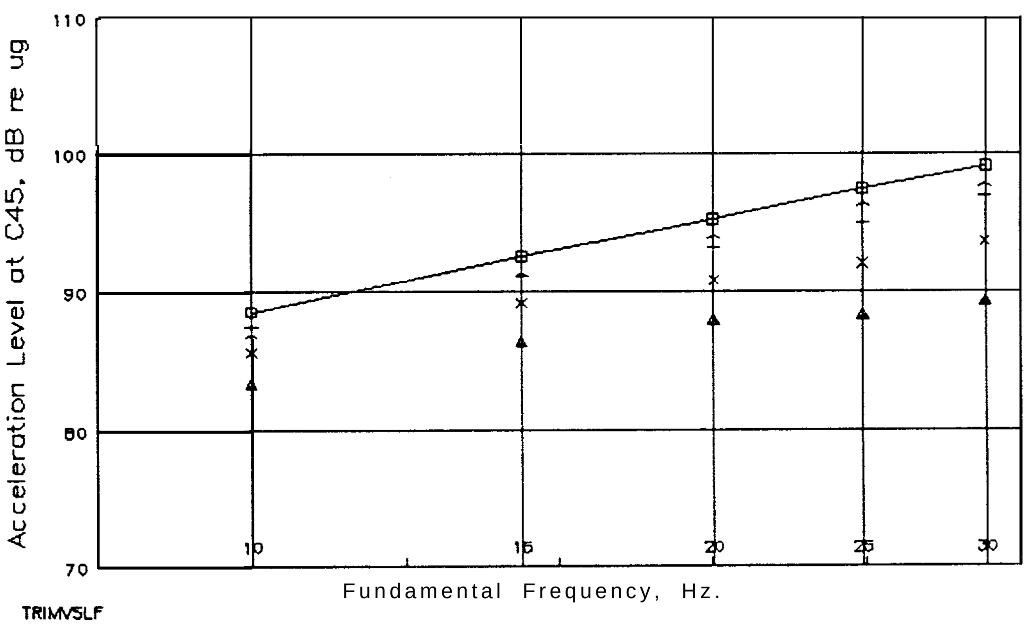


Figure 12
PMG performance vs. frequency. Fundamental frequency 4 Hz. Band levels;
Points measured at various settings.

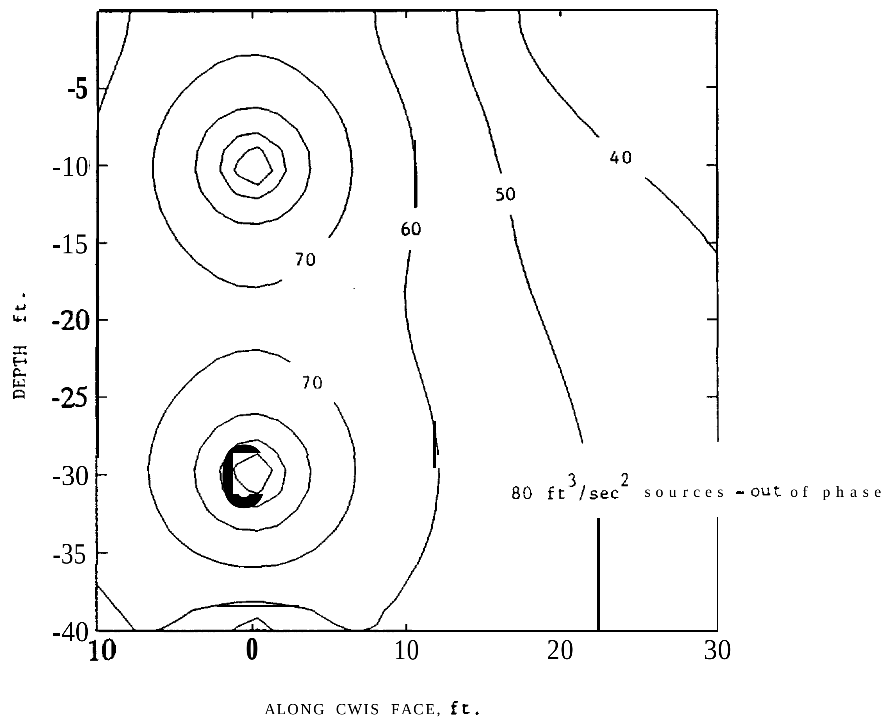


Figure 13
Estimated acceleration levels (dB//µg) before Salem Station CWIS.

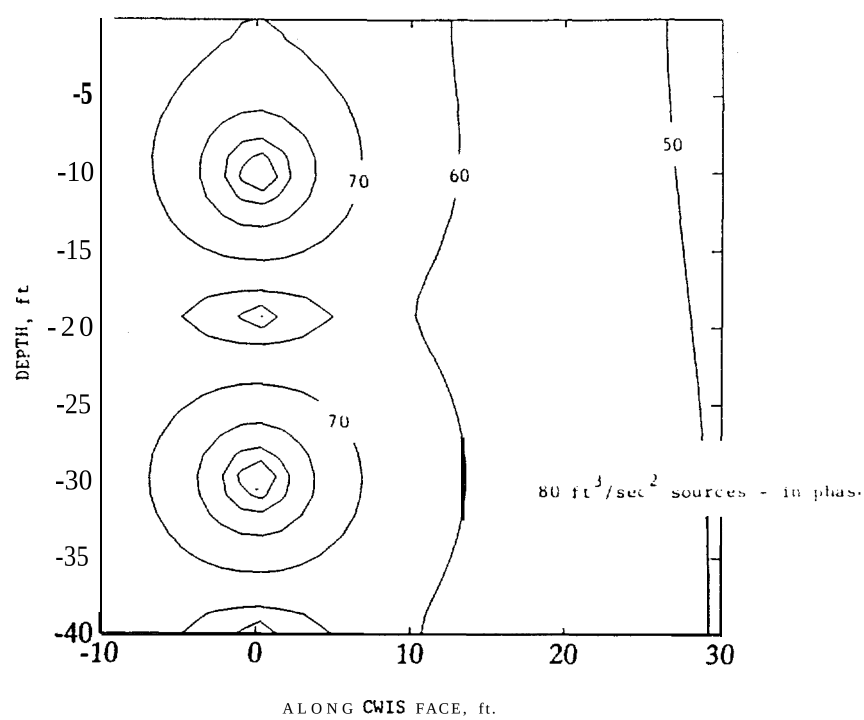


Figure 14
Estimated acceleration levels (dB//µg) before Salem Station CWIS.

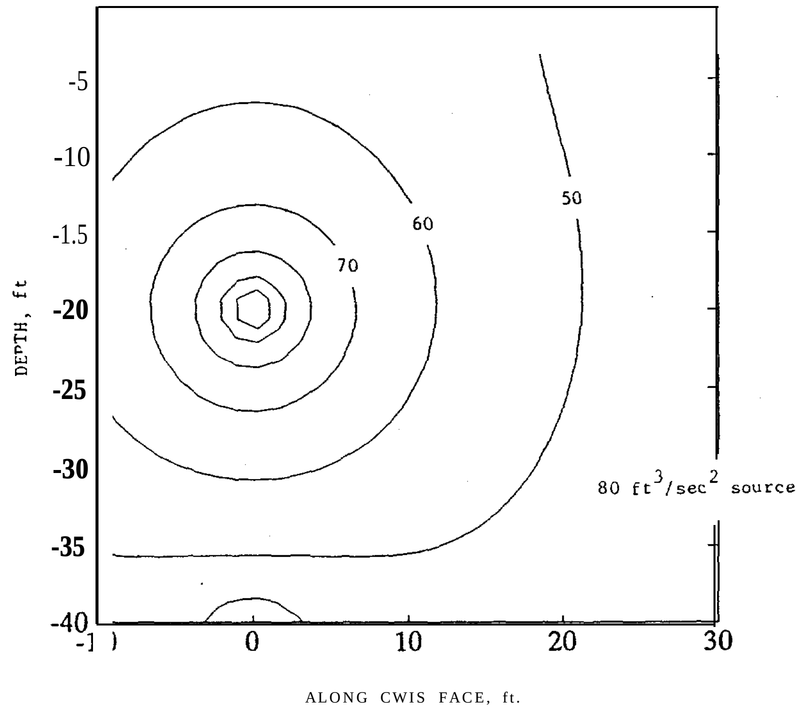


Figure 15
Estimated acceleration levels (dB//µg) before Salem Station CWIS.

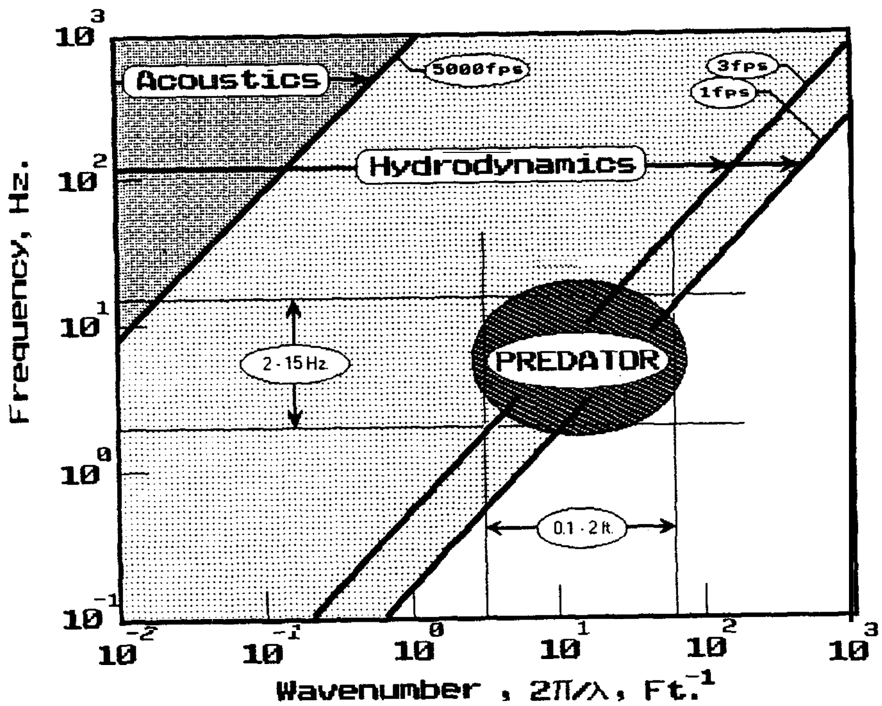


Figure 16
Predator signal in spectral space.

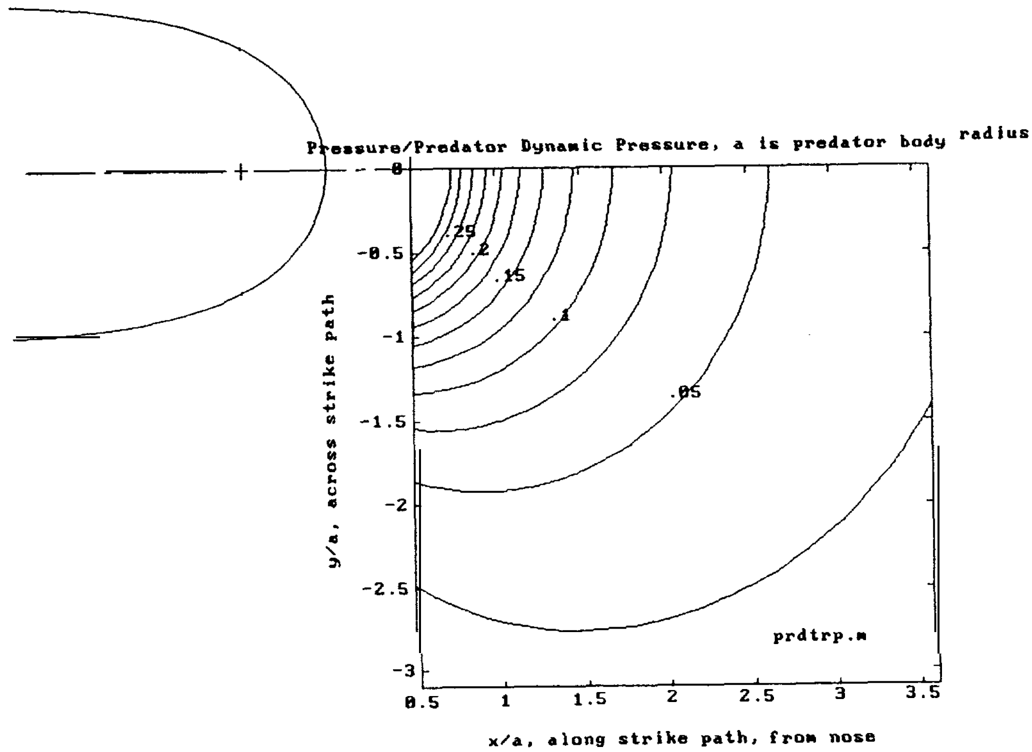


Figure 17
Pressure field before a predator advancing at constant velocity.

Question & Answer Session

MR. SCHILT: This goes way back to Ned Taft's part, and others here can address this a lot better than I. When you do a net pen test, you are asking a fish to make a choice between being here and being here. And so the fish needs to be able to observe differences between here and here. And since all aspects of the sound field are attenuating in a nonlinear exponential manner, the difference between here and here will be less different if you're far away than if you're closer. So I don't think that moving a sound source away from the pen is the same thing as turning the amplitude down.

MR. TAFT: Absolutely. It's not.

DR. BROWN: The original intention was to be able to reproduce the 20-yr-old result, where you could change the location and also change the intensity as it came out in the test pen, but with a different gradient. And we did a lot of that, but it got a little tiresome. So we actually ended up with our fixed location.

MR. TAFT: Yes. That was a logistical problem, because working out there in the open ocean was difficult.

DR. BROWN: But that was precisely the reason for that spot, stuck out quite a ways.

DR. HASTINGS: I have a question for Neal concerning the measurement of the particle acceleration, because a few people here have asked me some questions about that. This is not a true acoustic field. I mean, all of this 'infrasound' is really a misnomer; it's a hydrodynamic field. It's not propagating as an acoustic wave.

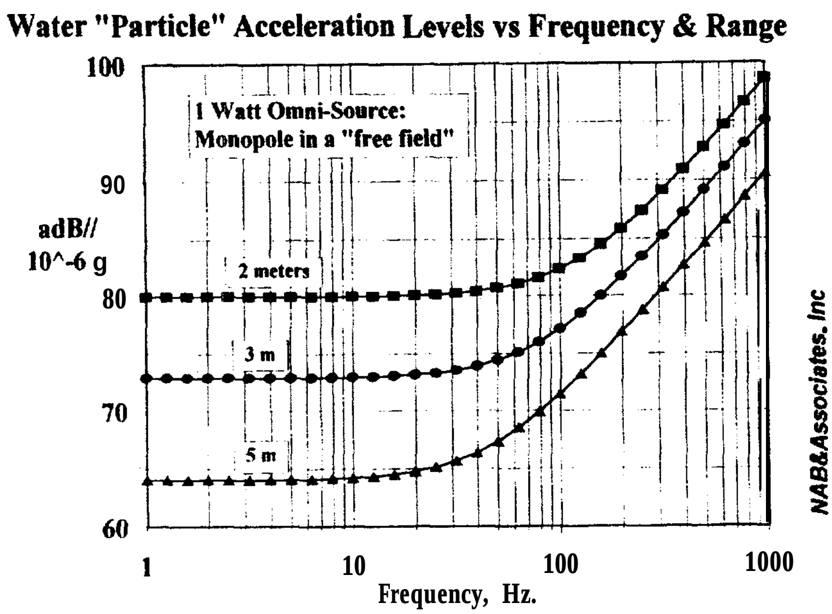
DR. BROWN: Absolutely.

DR. HASTINGS: And hence there's a misconception floating around that you can put an accelerometer in water and measure acoustic velocity. I just did a quick estimate, and your accelerometer would have to have a zero-dB sensitivity, would have to be able to measure 1 µG to be able to do that at 10 Hz for, say, a 100-dB sound-pressure level. And I just wondered if it is, in fact, that sensitive. If so, I think you could sell it to a lot of people.

DR. BROWN: We found that you could measure the noise of the system with the amplifier full on, 60 dB, down to something better than 80 dB below a G. So that's 40 on this scale, 40 db//1µG.

DR. HASTINGS: So it can't even come close to measuring true acoustic particle velocity. I just wanted to make sure that everyone realizes that.

DR. BROWN: You can if you get close enough. In the farfield, no.



DR. HASTINGS: I guess there is a problem here, because in my lab we work hard to try to create true acoustic wave, to create a traveling acoustic wave at 12.5 Hz. And that's infrasound.

DR. BROWN: Absolutely.

DR. HASTINGS: What you're calling infrasound is really slug flow. I just want to make sure everyone understands that, because you cannot stick an accelerometer in water, whether or not it's neutrally buoyant, and measure acoustic particle velocity.

DR. BROWN: You can do it at higher frequency. We do it all the time. Not at 10 Hz, because there isn't any. But the use of an accelerometer as a particle-motion detector at 1000 Hz or something like that is perfectly doable.

DR. HASTINGS: That's exactly because the acceleration is going to be proportional to frequency. So as soon as you get up into high frequencies, your acceleration increases proportionally.

DR. BROWN: You have to account for the densities, which this looks like water, the first order. By the way, everything I showed you was vector acceleration. It was not resolved in X, Y and Z.

MR. TAFT: I would like to add one thing. There seems to be a contradiction in terms of what was just said. We took great pains to go out at Salem and do our tests in the open environment, and then we went into a lab tank. We didn't want to put acoustic signals into the tank, but since we were dealing with particle motion which drops off very quickly, we felt the tank was an okay place to start. And relative to tanks and what Andy Tumpenny said before, I've been working with fish in the lab and in the field for 24 years. There's a very large difference between the way fish react in a current and in a stagnant tank. Generally fish are not in stagnant water, so you ought to be having a flow in the tank. You'll see in our tests that we actually did that.

Panel Discussion I

Defining research to support development of acceptable fish-guidance systems

MS. HARN: Your assignment is to define some research to support the development of acceptable fish-guidance systems. And in my mind, an acceptable fish-guidance system must demonstrate effectiveness over a range of expected conditions, both environmental and biological, that you might encounter, e.g., the target species, age, size, and species differences. And you also need to ensure that there are no inadvertent effects, none of the damage concerns that were raised earlier. Your budget is $200,000 for two years. If you have an idea, we'd like you to be able to report on the objectives and goals, i.e., what is the project and why do it, what kind of expertise will you need for it, and how practical is it to accomplish in two years.

First panel: Mardi Hastings, P.I., Tom Carlson, David Mann, John Holsapple, John Menezes.

Second panel: Carl Schreck, P.I., Dennis Dunning, Sheryl Coombs, Gene Ploskey, John Ferguson, Olav Sand.

Third Panel: Ned Taft, P.I., Richard Fay, Art Popper, Mark Mattson, Frank Knudsen.

DR. HASTINGS: Our panel identified four different targets and outlined them almost sequentially. Some of them could be parallel paths. (1) Identify effective stimuli, which are obviously species-dependent, with the idea of identifying effective stimuli for a few target species. Here in the Pacific Northwest, the target species would probably be the endangered species. This would need to take into account temporal characteristics of the acoustic signal as well as level and frequency content. (2) Evaluate the safety of that stimulus morphologically, physiologically, and behaviorally, because the issue with regulatory agencies will be the safety factor, especially where endangered species are concerned. (3) Determine how to generate the stimulus in the field, which includes a need to model the acoustic environment in order to have effective deployment at a specific site. (4) Focus first and foremost on safety, which is an issue in obtaining funds to actually install systems.

DR. SCHRECK: Our panel started out by defining what system would be ideal to guide fish, and obviously that would be some sort of universally applicable system. But we also decided that the folks out in this neck of the woods are more or less footing the bill for this workshop, and so we ought to concentrate on things that are more applicable to them. So we've limited the target species to salmonids and the life-history stage to juveniles, specifically smolts. And we asked the question, what kind of guidance systems are there that you could employ? Obviously the most common ones are physical barriers; others are acoustic, sound-source kinds of things; and there's also light, electric, bubble fences, etc. Practically speaking, because we are limited to a relatively small amount of money, and because the objective – at least in the Columbia

River system – is getting fish around structures, we feel that we must somehow couple a behavioral barrier with a physical barrier, as well as some sort of a guidance system.

So we came up with a protocol that we think might be doable roughly within the budget allotted, if we could get some help. And by help, we envision trying to get cost-share from other agencies, and also invite different vendors to test their systems. We would incorporate a product-development aspect into this and also, for the same bucks, try to evaluate other products that vendors might want to have tested in the system. We are thinking about finding a location with a couple of dams on it, not the Columbia River, but something a little more manageable so that you essentially have a model stream. And this model stream should have an upstream dam so that flow can be controlled as one of the variables. How fish approach structures is really dependent on the velocity and quantity of the water in which they're migrating. That's a very important variable that we feel needs to be controlled.

We would also look for an alternative site that provides depth as a variable. How your fish respond to guidance, e.g., do they go left or right or up or down, can be important. So we need either a place where we could regulate depth or we need two places, one deep and one shallow. The ideal would be basically to introduce a research station at the upper end of the site, and give the fish several miles to migrate down to the structure. This structure would basically be a barrier dam with a physical fish-guidance capacity built into it. Obviously we didn't have time to flesh out exactly what this ideal site should look like, but it must allow us to test an acoustic guidance system and perhaps lighting as a possibility.

The idea then would be to have fish migrate to the structure, to see how they move through the area that you want them to move through, when things like sound and/or lights are on. And it is obviously also important to check the health of the fish once they have passed the structure to make sure there aren't any long-term negative effects. Within the scope of the budget, I think that could be done if you do 'general health' sorts of examinations, 'clinical parameter' types of things, but also monitor the migratory behavior of the fish downstream. In other words, not look at just how they approach the structure – do they hang out a long time above the structure rather than pass it freely or do they go left or right or up or down? -but also is their migratory behavior affected downstream when the sound source is on vs. off? So during the first year of the study, a fair amount of money would need to go into developing the sound source and then more or less field-truthing it, and hopefully the second year would be used to do it right.

Basically, the team that we would need for this would consist of general fish biologists and some behaviorists who could give us a clue if the fish were behaving normally or the way we would want them to behave. We would need a hydrologist to map the actual water flows that the fish were encountering and basically 'type' the habitat that the fish are migrating in. We would need people to monitor the acoustic fields and describe the nature of sounds the fish are experiencing. We would want physiologists to determine other kinds of sensory inputs that might be influencing the fish, such as lateral-line systems or whatever. In other words, as they approach the structure, are they using vision, are they using pressure, what are they using to sense its presence? And we would need statisticians as well.

DR. SAND: We also discussed the necessity of spending other resources in developing a sound source, because an adequate sound source is not commercially available today.

DR. MEIER: I'm Sandra Meier with ESEERCO. Given that you want to capitalize on your money and on your experience, I would remind you that a third of your funding for this workshop is from east of the Mississippi. And the reason that ESEERCO is here and very interested in this is because we think it's time for cooperation, both financially and scientifically, between east- and west-coast scientists. Although our fish may be different and less important to you, there is a wealth of information available in the east. So when you think about money, and when you think about your team, please remember that there are many folks sitting on the Hudson River, which has dams and water control, who could benefit your program, and they would benefit too.

DR. SCHRECK: That's a good point. What I failed to say is that our approach is to hopefully design generic tests, which is why we didn't pick a site on the Columbia River. What we hoped was to use this as a model stream with salmonids. Because of the amount of money, you can test only one thing, but hopefully it would be applicable anywhere in the world.

DR. MEIER: And a lot of the folks in New York have done it.

MR. TAFT: Our panel immediately decided that the Northwest, specifically the Columbia River, should be targeted. That was not a majority vote. I guess we were more constrained than others by the $200,000. We said, we'll make it half a million, and we were still constrained by that. And while we talked about the sound source, we didn't identify development of a sound source as a priority. I think suitable surrogates can be developed in the short-term to evaluate fish responses to what's coming out of those sources, and then worry about the development later. I will tell you personally, $200,000 will not develop a sound source in a year or two years.

One of our goals was to identify stimulus by species. And as I said, the group decided to narrow in on salmonids, specifically those in the Northwest. Some key things that emerged were to specifically identify frequency and signal type. Then we got hung up on the scale of what could be done. We talked about flume studies, we talked about selecting a water course, a river or stream, that's more natural and putting in some type of device. I brought up the point that we would probably have to build a dam and a facility, and nobody thought that was a good idea. But I think that is what you are actually talking about, building a structure that would serve as a pilot plant, essentially, on a smaller scale.

DR. SCHRECK: For $200,000, you aren't going to build anything, so you would be forced to find something that existed.

MR. TAFT: Or something similar to what was done on the Umatilla River this year, which was to find a small water intake with the right features; for instance, two side-by-side bays with the proper hydraulic characteristics, maybe some of the background noise that would occur at a large plant, although I don't think you would find anything like that. We also talked about combining devices, looking at things like sound and lights in combination, since that seems to have a lot of potential. And also perhaps delving into identifying the acoustic environment at existing projects.

The sense I got from our discussion is that we're getting closer to knowing what kind of energy can be put in the water to make fish do something. And we know that there's a lot of background noise and complicated hydraulic and acoustic factors in the environments around these plants. I think where we bogged down was, How do you bring those together? But we thought for a 2-year program that a smaller-scale approach was the way to go. And the idea of any basic research never came up.

DR. POPPER: Looking at this as someone new in the field, I was interested in thinking about how we could do something relative to diversion above the dam before the fish become entrained into the whole scope of the complexity. John Menezes used the term 'line of sight' which I had not heard relative to a dam. I thought he meant how far away the fish had to be before it could see the dam. Knowing that was a couple of inches, I realized that wasn't quite what he meant. But working above the dam to see if we can do something there to prevent the passage problems in the first place might be something worth talking about. We agreed that it would be very expensive, but it might be a more constructive way to go.

One of the issues that came out of John Menezes' talk yesterday was whether we could take advantage of the acoustic parameters right around the trash racks in the guidance thing. We didn't come to any real conclusions, but at least those were two approaches we thought might be worth exploring.

MR. TAFT: I don't know whether we had agreement on it, but I raised the point that there has been a lot of work done with surface barriers to try to get fish around things and into bypasses. And in many cases the reaction of fish is to sound. Similarlv we've put screens in the gatewell slots to divert fish back up again, and they go under those. If the fish keep sounding and wanting to go down, why don't we keep them going down and try to figure out a way to get them out of the bottom rather than the top? They obviously have a propensity to go through the turbines, which are relatively down. But I don't know how you would take 200 ft of head and put it into a bypass pipe.

DR. SCHRECK: We thought that concentrating on salmon smolts allows you to use them as surrogate species for other animals with similar life histories. We're dealing with guiding a migrating fish that is motivated to move downstream rather than a fish that is being passively sucked into something. They're two very different problems. So we thought that perhaps what we learn with salmonids here would apply to other anadromous or migrating fish.

MR. HOLSAPPLE: I'm **John** Holsapple with ESEERCO, and I'm interested in the safety issue which came up in our group. We liked the idea of cost-sharing to develop a bigger program; however, we tried to stick to the $200,000/year hypothetical restriction. Is it possible that you could develop a 2-year program limited to $400,000 that in fact would answer the safety question in an adequate fashion? We have two approaches, one of which would be to look at physiology, things like sensory cells. This would seem to require a fairly substantial effort at a fairly substantial cost over a longer period of time than 2 years. Or do we look at it from a behavioral standpoint, exposing fish to various doses of sound to determining whether there is a safety issue from a behavioral standpoint. Do we have any evidence right now that there is in fact a safety problem? My question would be addressed to my principal investigator and to Dr. Popper.

DR. HASTINGS: My answer is based on a paper I wrote when I was at Bell Labs a few years ago and on the sound-pressure levels I've seen presented here, and that Art Popper and I have looked at a 'hearing generalist' in which we saw no damage. These were nearly traveling acoustic waves, and we saw no damage until we hit 180 dB//1μPa at lower frequencies, in a continuous tone. When we pulsed for a l-hour exposure, we saw no damage at all. That type of exposure would more than cover a fish passing something. We took samples from every area that we thought might be affected. When you go up to a more sensitive fish, I can tell you from experiments I've done with gouramies, for instance, in which we couldn't do the experiments because we would acoustically stun them very quickly with very short-term sounds on the order of, say, 190 dB//1μPa. And, in the course of some time-period, we tested a lot of goldfish and found no effect at all. These were pretty high sound-pressure levels, but we had wiped out sensory macula. Behaviorally, the fish still swam around in the tank. It's verv hard to assess behavioral changes in the lab if you have caused hair-cell damage because the fish will not be responding to things in the natural environment. So we have made the assumption that you do not want to damage hair cells. And recently we also looked at this post-exposure thing wherein the damage is done but it doesn't manifest itself for a few days. It's a well known fact that fish rely on sounds and hearing, whether we call it hearing or detection of hydrodynamic and acoustic signals underwater. And if you destroy any part of the sensory system, I think that would raise questions about a safety issue.

DR. POPPER: First of all, our orientation is the effect of sound on the octavolateralis system. That doesn't mean that other things aren't being damaged, and I think the question must be asked, what is your most sensitive measure of the effect of the sound? That is, should we be looking at the octavolateralis system, the ear and the lateral line, or should we in fact be looking at the effect on the liver or the kidney or things of this sort? I don't have an answer to that, although no one has ever asked that question, to my knowledge. I'm collaborating with a friend of Carl Schreck's, Yonathan Zohar who is at the Center for Marine Biotechnology (COMB) of the University of Maryland Biotechnology Institute (UMBI). He's supported by the Navv who are reallv interested in this exact problem. In fact, this problem is broader than our interest and the Navy's interest in it. People doing ATOC studies are asking if we're affecting the fish that swim by the sound source. Yanny is looking at stress levels, hormones and things of this sort. That may be a more sensitive measure, I just don't know. If I raise my stress level, is it going to kill me tomorrow or not?

The arguments I'd use for working with the octavolateralis system, at least at this stage, is that it's direct damage to the detection, and that stress levels mav not be a factor; although certainly if you lose the receptors very quickly, you're talking about a dead fish. If the fish swims along and loses his receptors, he becomes a prey. So I think that's maybe one of the more sensitive measures.

Your question really was, can it be done in a couple of years with a couple hundred thousand dollars? Our study took four of us about a year, involving reasonably heavy time by two of the people, half time each. It's not something that you can automate. It means looking and making some intelligent decisions using an adult blind system, so you don't know what you're seeing. With what we know now and with proper selection of species, I suspect that over 2 or 3 years, the answer is that we could at least be far more advanced than we are now. Will we have all the answers under all the conditions? No, that's not going to happen. But at least we could, especially after hearing what we have heard the last couple of days, probably say that these are the sounds, the parameters, the animals, and have a much better guesstimate for our use 2 years from now than we have now.

DR. DUNNING: I would like to respond to Art's comment by pointing out that we have to be very careful with what we do, for a couple of reasons. First, if the 'null hypothesis' is that there is no damage, it's virtually impossible to refute. If the damage isn't done to the octavolateralis system, it's the kidneys; if it's not the kidneys, it's something else. When do you get to the point of saying, I've looked at enough things. If there is damage to the hearing system, we're not even sure in alewives what system is detecting the sound. I think most people would agree, we don't know whether it's the swimbladder, whether it's the ears, or it's something else. My approach would be to look at the organism and its behavior and determine if it changes. We subjected alewives to high-frequency sound for up to two and a half hours, and they were repeatedly exposed between 500 and 1000 times and showed no change in behavior. So, if there was damage to the sound-detection system, it wasn't readily obvious under a very extreme condition. I'm certain that exposure to some high sound-pressure level, for a long enough time period, can probably induce some damage somewhere. It's like cancer. If you give an organism enough carcinogenic material for a long-enough time period at a high-enough rate, you'll induce cancer.

The question that I have is whether you start out saying that there are certain expected exposure periods in the field and then test those in the lab, or you go to the extreme condition in a lab where you damage an organism and then work backwards and say, do I expect to see that in the field? As an applied biologist trying to figure out how to deal with resource agencies in trying to keep fish out of intakes, I think a very practical approach is to work with the whole organism. That is, expose fish to extreme conditions and see if they continue to respond to sound.

DR. POPPER: I don't disagree with that at all, because you do want to look at the behavior of the animal. But at the same time, you are dealing with animals that are constrained and they may actually be at a disadvantage. You may not see what's happening to them. The animal may survive perfectly well in your net and in your cage, but once it's out in the field and subject to predators, it may be in a situation where the animal actually has some disadvantages because of something that's happened.

DR. DUNNING: At Fitzpatrick, fish would approach the field until they were able to detect it and then continued around it. They didn't stay around, and they were not constantly exposed to that sound for extended periods. Nor did they get to the point where they were close enough to the transducers to be exposed to what we would consider very high sound-pressure levels. I think they were reacting at the point where there was a minimum threshold. I suppose you could hypothesize that the minimum threshold is where the damage occurs, but that seems unlikely to me.

DR. POPPER: One of the concerns that I've had is not the animal you are worrying about not controlling, but everything else in the area. What happens if you are in an area where there are fish eggs or where there are fish that don't move around much because this is their territory or something of this sort? The question is not just the animal, the clupeid or the salmon, but it's everybody else in the area. I'm not sure that just looking at the behavior of the clupeid will give you all of the answers.

DR. DUNNING: What Art just said illustrates my fundamental concern, that the null hypothesis is no damage to the organism. The null hypothesis just got larger. It's not simply the organism anymore, it's everything around it. At what point do you say, I've looked at enough things to reject the null hypothesis? But from the perspective of someone trying to deal with resource agencies, I think we have to get to a point where we say, what are reasonable questions to ask? If we have to determine if damage occurs to every organism that could be exposed to sound, it's highly unlikely that systems like the one we're going to use at Fitzpatrick would get installed. And in the process of waiting, a lot of fish are going to get killed.

So the trade-off you make is, do you want to take an action that you think is prudent and save fish in the short-term and address specific questions later, or do you wait until you're absolutely certain that you've rejected the null hypothesis that there is no damage?

DR. SCHRECK: It's the great 'less filling' sort of thing. But my lab spends a huge amount of time trying to address this sort of question of fish health and well-being after you have done something to them. And I think the answer to the first question, if you can do it within a 5200,000 budget, given everything else that you have to do, is probably no, other than on a very superficial level. However, I think you're very right if we're dealing with sites where the animals are moving past a fixed area where we're not so concerned with a huge number of non-target species.

For example, at the face of many dams and so forth, where you maybe don't have a large number of non-migratorv fish, I think the real proof is, do these animals survive to reproduce? And you can design subsequent tests to evaluate that. However, with most species if your're dealing with 6 or 8 years, you can't wait for the results to come back. What you can do, though, is use subsequent behavior as a very sensitive index. And if you're worried about things like predation and the possible negative effects of structural damage on how the fish performs its other necessary life tasks, you can get at an awful lot of that by behavioral observations after these fish have passed your test system. Say, for example, radio tags stop moving, or wind up in the air; that tells you something. So you can go a long ways, if you're smart in designing your primary test on the fish behavior, using subsequent behavior, and it integrates all the negative affects of stress on physiology as well asmorphological damage. But the ultimate proof really is, do these fish come back to reproduce?

MR. TAFT: In the flavor of this exercise, I don't disagree with anything that's been said. But from a different point of view, and if you're talking about the near term – the first year for whatever money there is – you need to identify what signals you are going to expose them to. We don't have a good handle on that. We've got a little information, but it sounds like everybody thinks we've got the answer and now we're going to go in and start looking at a physiological level. And I don't think we're there yet. That's just from a practical point of view. If you had infinite money, you might do it all at once. You would look at eggs and crayfish and everything else in the water.

DR. FAY: I agree with you completely. It seems to me that, as a general health issue, if you could determine the most effective stimulus, then you could lower the sound-pressure level. If you were working with a signal just because of the transducer you inherited or the one that's cheap or whatever, or if your intuition was wrong about what the most effective kind of signal is, and you have to raise your level 40 dB above some kind of more ideal stimulus, then you're putting these fish at risk, and they don't have to be at risk. So I think some systematic work has to be done to determine the kinds of signals, the frequency temporal pattern, for example, that are most effective. As a physiologist, I know that the kind of signal that drives the nervous system crazy is the amplitude-modulated signal, with particular amplitude modulation rates (30-60 Hz). And a pure tone at the same sound-pressure level may cause no physiological response whatsoever. Just amplitude modulate it a little, and the nervous system goes wild.

And so it also seems to me that it's a question of whether these fish, when they avoid a sound field, are avoiding it because it is annoying, frightening, or damaging. Some sounds we avoid because they're annoying, and some sounds we avoid because they're painful. It's conceivable that those aren't necessarily the same sounds. It's conceivable that the fish may avoid sounds that aren't necessarily painful but are just fantastically annoying, or frightening, without necessarily being damaging or really painful. At any rate, I think some systematic work must go into figuring out what kinds of signals are most effective in any given situation.

MR. TAFT: There were certain species that we tested with these low-frequency devices in a long-term exposure in the lab, and because they were limited in numbers, we had to test the same fish over and over again. From pure observation, we were beginning to wonder toward the end if we were damaging them, because the ones that were subjected to it over and over again didn't look happy at all. And the guv who was doing a lot of the work kept saying, "This group's burned out," and we couldn't use them anymore. And that's stuck with me.

MR. BROWN: The stock answer to your question, Dennis, about whether it causes cancer has always been that in this country, we need stronger white mice. That's one point to start at. But this may be heresy. I'm neither a biologist nor an engineer, I'm an MBA. From from an industry standpoint, there must be a return on investment for any of this testing. So if I had a limited amount of funds and 1 was trying to maximize my return on investment, I would take it from the standpoint of where do you have substandard performance in existing physical barriers? And I would use it as an enhancement for existing physical barriers and try to replicate that. I would think that's the fastest way to accomplish several things. Number one, save fish, or more fish. And number two, build an infrastructure or a base that industry can drive off of and get to a commercial type of foundation.

DR. SCHRECK: I think that's exactly right, and it gets back to what Dennis was saying. I think it really matters, the lesser of two evils perhaps. I don't think it's necessarily essential that whatever guidance system you put in is strictly benign. It has to be more benign than not having a guidance system there. I also agree with Dick. I think the response is going to be graded, and it depends on where the animal is in terms of being guided. In other words, you can have psychological sorts of things that are detrimental, you have the other end of the extreme where you have actual physical damage, and then there's everything in between. And they all could have negative effects, it just depends how much. The psychological impairments can leave the animal vulnerable to predation and so forth. But it's a graded response.

DR. DUNNING: In response to your point, Ron, I think this is not too unlike the drug industry. The fact of the matter is, if it takes you 10 to 15 years to get a drug through the development phase and approved, you may be very reluctant to spend the money to do that, which seems to be happening to many drug companies. And the point that I was trying to make is that we could take systems that seem to be effective and put them in the field and then do additional testing to try and address specific questions about damage. Or do you need to look at all the questions about damage first before you install the system? And so Art and I really aren't arguing too much in terms of what you should look at. I think where we differ is in terms of sequence.

MR. BROWN: I just had a very interesting conversation comparing the salmon situation, or any other endangered species, with that of the AIDS crisis. We need to accelerate this particular type of lead time and save these fish, and find out what the long-term consequences are. But the first thing is, it's got to be better than the alternative.

DR. POPPER: I'm not disagreeing with you at all, by the way. I don't think we need to wait until we get these results to put something in the field. I think we need the data. Because at some point you're going to be asked that question. It mav not be today, it may not be tomorrow, and you can't stop what you're doing. I wasn't suggesting that. I think you do need some data, very selected way, to at least get some guidance as to the parameters. That's all I'm saying. I wasn't saying every sound, every fish, every age, etc. But you do need to get some data, which we don't have right now.

DR. TURNPENNY: I would like to concur with Dick Fay's point that it's important first of all to select the appropriate signal to make sure that you're not using more power than you need. Of course, whatever signal you choose, the risk to the fish depends on how you put it into the water. And if you have one booming sound source, then there will be a point where the fish gets close to it and it will be at high-level. The way around that is to design systems with a large number of smaller transducers so that you limit the risk at any particular point, and that's a management practicality that can be achieved.

DR. CARLSON: The situation with sound may not be much different than other exposures that fish face at hydropower projects. For instance, turbine passage is one that springs to mind for me. And there the protocol for evaluating the damage done to fish is to release fish and recover them, and then to look at what was done with them. The things that are looked at to estimate damage reflect the history of people who have worked with fish. Descaling, for instance, indicates certain things to a biologist about the health of the fish. So one of the things thatmight come out of physiological work is to learn what we need to look for as a measure of damage to fish so that we have something that we can look for. Then we can worry about how we expose them, how we recover them, what we do with them. Right now, I'm not even sure I could tell somebody what you would need to look for.

DR. NESTLER: You're on one side of the dam and you have recovered a fish that's cut in half, and you look at that fish and realize that it's probably going to die. And then you go on the other end of the dam, and you're actually able to shoo the fish away to the other side so it doesn't come through the dam and doesn't get cut in half, and you're so excited and happy because you've made progress. So some of this is almost a human-nature response to the issue. Quite possibly, some fish are damaged by loud sounds, but we seem to have some success at preventing damage that fish would incur going through the dam, and it gladdens our hearts.

MR. SCHILT: Maybe with a system like the Columbia where you have a salmon smolt that you're worried about, and you have a candidate sound that you've shown in some controlled way to be effective, and you have some sort of reasonable estimate about how long the animal might be exposed to that loudness of that signal. Then you could experimentally subject a significant number of those animals – or if it's an endangered species, maybe some surrogate for those animals – to a test to determine what they use their hearing system for, e.g., orienting the flow, catching live prey, avoiding predators. And you could go into the laboratory and ask if this fish can orient to the flow, and maybe with some reasonable number, on a scale more like somebody's master's thesis, you could make a contribution.

DR. SCHRECK: That's exactly the sorts of things we do. I would add disease resistance to your shopping list, just within the context of the $2000 that are left after we have done all of this.

DR. BROWN: I think in this game you've gotten ahead of the issue of what underwater sound does to humans. We conducted a cursory survey relative to the Salem station on the notion that one must have divers in the water to deploy and maintain some of these systems, perhaps while the sound was on. And we asked a number of authorities and got no answers. Finally we got sort of an answer from someone in the Bureau of Naval Medicine. It was less than we had, I know that. But the degree of knowledge about effects of intense sound on submerged humans is very small. And you may be able to multiply your program by a big number by tacking it on to a human study.

DR. POPPER: There was one point about two years ago when the Navy shut down all their diving because of an explosion in the Mediterranean off France, which reportedly killed or injured a diver, until they could determine what had injured or killed the diver. It's become a big controversial issue. The other issue is marine mammals, where the Navy (ATOC, Acoustic Tomography of Ocean Climate) and we want to put a sound in the water for six years and keep it going off California and then off Hawaii. What is stopping it right at this moment is the question of possible damage to marine mammals, presuming they're anywhere within the vicinity of the sound source. It's gotten to the point where they were actually turning the sound on a couple weeks ago, but three humpback whales were found dead at about the same time. And that's literally stopped the thing in its tracks. They claim now that the sound wasn't the cause of the damage to the whales. But anything underwater affecting sound has become a big thing. Of course, the worst source of sound underwater is humans.

DR. NEDWELL: There is, in fact, a large U.K. program at the moment on the effects of pure-tone underwater sound on humans which I'm involved in. Some of that information is already published and will all become available in the next month or two. There are two prime ways in which people underwater can be injured. The first is auditory damage: the human ear does work underwater, it doesn't work as well as it does in air, but nevertheless it works reasonably well. The second is the air-containing structures of the body, e.g., the lungs, sinuses, middle ear, anything that contains air, basically because it translates pressure into velocity and sheer of tissues. The actual levels needed to cause damage are very high.

DR. DUNNING: I would like to embellish a point that Ned Taft made earlier, about $200,000 not going very far. At the risk of sounding like I'm not a very good consumer and I don't know a good deal when I see one, I want to tell you what it cost us to take the concept of testing alewives with high-frequency sound from a quarry through reconnaissance at a field site and then do two subsequent field studies. It cost ESEERCO a little over $1 million to do that. And that partly has to do with the fact that we're dealing with highly sophisticated electronics, with systems that must be modeled. To give you an idea of what it takes, ESEERCO made a $1 million commitment over three or four years to take one sound on one species and develop it into a workable technology. So when Ned Taft said $200,000 doesn't take you very far, I just wanted to give you some perspective on what he meant, at least from what I have seen.

DR. FAY: I would like to point out that people who work at universities, particularly arts and sciences universities, mainly make their money by salary and are promoted and tenured based on their research. And so the opportunity for one of them to write a paper in a peer-reviewed journal is worth money to them. And so in that sense, they may be a cheap source of labor. But the key here is that these people have to be given the opportunity to take part in a project that will actually lead to a paper in a peer-reviewed journal; otherwise, it means little to them.

DR. NESTLER: I would suggest you use the word 'cost effective'.

MS. HARN: I would like to speak in defense of the $200,000 exercise. The idea behind this was not to necessarily develop an entire system, but to do some targeted research that would help to make systems that are under development more acceptable. And the $200,000 figure, for two years, that's the kind of money that Art Popper's lab seeks. You wish you had that much. So the idea here is to talk to these laboratory people and see just what they could do for those of you trying to develop acceptable systems for guiding fish.

MR. MENEZES: The comment was made that perhaps leveraging university efforts might be an appropriate way to go. I don't think that selecting one ear, nose and throat specialist or one subsystem specialty would result in a solution, regardless of the kind of cost sharing or investment. My feeling is, as I indicated in my viewgraphs yesterday, that solving this problem will require a team effort from a group consisting of members who have never before been assembled. Although getting something published in a peer-reviewed journal may be financially fulfilling or career rewarding, I think the key is not so much that the results are reviewed by one's peers but rather that they're reviewed by other subsystem specialists who can take the information you've gleaned and take it to the next step. Many people are fairly successful in pursuing their own little niche areas, but I think this is going to require something much more global than that. And what's missing, and what I hope to have happen, is better technical information exchanged between the groups for some continuity.

DR. POPPER: The bottom line is that, as chairman of a university department, the way I promote people and the way they keep their jobs is through publication in peer-reviewed journals. If they don't do that, they don't have a job, they don't get promoted or get salary increases. So it's a very different environment. It's not that what they do is taken somewhere and applied, but that their work has gone through the peer-review process and been accepted. So I think it is much more important than you suspect. But I agree with you completely, and one of the reasons for this workshop is to generate communication between the groups who are taking different approaches. I think we're accomplishing that.

DR. SCHRECK: I'm a university researcher, and my lab encompasses studies that go from the molecular level in test tubes all the way to 500-mile-long study sections of the Columbia. So we have a good feeling for the cost of some of this. And if you do a laboratory study and then scale it up to a small field study, the small field study is probably an order of magnitude larger. If you go to a field study like the Willamette River, you may be another order of magnitude larger; if you go to the Columbia River, you're another one or two orders of magnitude on top of that. So I guess I wouldn't really disagree in terms of the university versus non-university, but I think it is really a matter of where you want to do your test. And if it's in a test tube where you can control a lot of things, it is very, very cheap compared to taking it out into a river system where you're into a whole different mode of operating, just in terms of staffing, safety, boats, that sort of thing.

DR. POPPER: You can also ask separate questions, or you can ask questions in a much more controlled environment.

DR. SCHRECK: They're both important.

DR. POPPER: They're both extremely important, and they should be complementing each other.

DR. CARLSON: If we use history as a guide, laboratories have generally been used to enhance our ability to observe effects, so that we know what to look for and how to measure it when we go into the field. I don't see any inconsistency in this area, in going back to that model.

DR. SCHRECK: It's highly desirable. The lab allows you to choose the questions that you want to ask in the field in a very cost-effective way. You can screen a whole variety of things in the lab very cheaply.

MS. HARN: And you can take the field observation and try to bring it back to the lab to understand it better and make sure that, given your field observation is in the context of a very complex environment, you really know what's going on.

DR. CARLSON: If you want to follow that line of reasoning, where are we now? We've exposed a lot of fish to a lot of sound. We have some observations that we would like to follow through on and perhaps scale up. So maybe now is the appropriate time to take one or two of those more promising sound signals and try to determine, based on our understanding of the morphology and physiology of the hearing system, whether or not there's damage through exposure, given those particular parameters.

MR. HENDERSON: My name is Jim Henderson, and I am a technical consultant to the Navy in underwater acoustics. We just finished a project at Lake Pend Oreille in northern Idaho, which is the Navy's premier acoustic research & development facility in the United States, and we were specifically interested in the effects on a fish called the cockanee from specific frequencies relative to insonification of these fish and something the Navy wanted an active source that they were putting in the water. We brought together a panel of individuals to review a study proposed by the University of Idaho, one of whom was Dick Fay. We put together a number of inputs from experts in the field on insonification of fish, and then exposed the cockanee to predators who had been insonified and all of the things associated with doing the appropriate kind of a test with statistical significance and such. And we conducted open-lake tests, insonifying fish with projectors that were anywhere from 500 to a few thousand feet away at very high-source levels. This was at a Navy facility and so we got all the acoustics essentially for free. But it cost about half a million dollars to do this kind of a study over a year and a half. The problem is that when you talk about getting into peer review, and the University of Idaho has faced this, they found no impacts. And so while the peer-reviewed journal said this is really a neat study, we're not going to publish it because we didn't find anything, and there were a number of other things out there that did find things and so they can't get in.

Also, a number of the fish that you're trying to divert in the Columbia River system come out of hatcheries, and these hatcheries are extremely automated by different kinds of rotating machinery. We've made comparative measurements between those hatcheries and the natural environment, and found, depending on the hatcher!: the measurement venue, anywhere from 65 to 100 times more energy in the hatchery, between about 20 and 600 Hz. And so I think that potentially 80 or 90% of the fish that you might be trying to divert have a prior exposure from essentially day-l in the hatchery until the time they are released. 1 think this is a 'real world' problem that needs to be looked at.

DR. TURNPENNY: Two of the groups here talked about working on a reduced scale, and it seems to me that there is a significant risk in this. The papers that we have heard yesterday and today have shown that effective guidance of salmonids and other species can be achieved, generally on a much smaller scale than the Columbia River. This is the biggest risk 1 see: If you have a small-scale situation, it would only take a momentary decision, perhaps a single flexure by the fish, to get from one point to the other. If you extend the scale of that, then the fish has to sustain a behavior pattern for a period of time. And if you extend that from a few seconds to a few minutes to maybe 30 minutes for a fish to cross from one side to the other to get where it's meant to be, then there will be a whole load of other possible interactions that must be taken into account. Also, you may even get habituation over that time with some of the signals we've seen. So I think there's a significant risk associated with any scaling down that needs to be considered.

DR. SCHRECK: Our concept was not to scale down from the Columbia River into something really small. To give you an idea of how far some of these smolts travel, they average probably 2-3 miles an hour continuously.

Panel Discussion II

Issues involved in applying acoustic technologies

DR. NESTLER: I think the best way to preface all of this is to say that the first panel was primarily academic in nature, and they identified lots of problems, lots of questions that needed to be addressed, and lots of issues, which was what they were supposed to do, as far as I understand it. The members of this second panel are primarily people who can present at least some evidence that we've actually guided fish, and, based on that track record, can address issues like how long did it take us to get there, how much did it cost, what are the difficulties in applying this technology to different sites, and related kinds of questions that are much more applied in nature than what the earlier panel presented.

DR. MANN: I had a hard time, from what was shown in a number of the presentations, believing that anything happened. And I think, there doesn't necessarily have to be one approach, but I think a logical approach has to be taken. When there's on and off conditions, does everyone do on/off? How do they statistically compare them, and that sort of thing?

MR. TAFT: Part of the problem of understanding is that we didn't have much time to present it, and so you got a very cursory overview of what was done. I think this is true in everyone's case, and I guess it is a concern. As in anything, it's nice that people replicate results. That's why we started our lab studies with what Frank Knudsen was doing at the same time, to try to replicate that and use similar methods. I think this approach will evolve as this relatively new information becomes available. People will start reading each other's information, through workshops like this, and we'll learn more. Some of it is gray literature, and I know some people won't even look at it, but that's the reality. And I agree with you that it's important, as everyone proceeds, that we try to at least define what we're doing, if not do things in a similar mode. Otherwise the results are not comparable.

DR. SCHRECK: What should be the experimental unit? Is the individual fish the experimental unit, or is the replicate the experimental unit? Because you have followed the leader effects, even though you're using huge numbers of fish, it's very possible that your sample size is something. How do you handle that sort of circumstance?

MR. TAFT: From my own experience, I would never test one fish, ever.

DR. SCHRECK: But even if you had a thousand fish in a net pen or a stream, if you have a follow-the-leader effect, the first fish affects everybody else, and they do the same thing. So it's a sample size of 1, perhaps, and how much replication do you need and how do you get it?

MR. TAFT: We consider the test group to be replicate. I don't know what others did.

DR. SCHRECK: So the experimental unit is 1?

MR. TAFT: Right, regardless of how many fish. And we always tried to use groups of fish that represented the densities in which they occur at the location where they were a problem.

DR. DUNNING: Maybe I can address your question, Carl, in a slightly different way. When we went through the process of testing alewives, the first thing we attempted was to see under controlled conditions whether you get any kind of strong directional avoidance response. You can characterize it any way you want, but you visually say, yes, it's strong, which is what we did. Then the question was, if you get a strong directional avoidance response, is it repeatable? When you convince yourself that it's repeatable, you ask, can I use this behavior to exclude fish from some area, which is what we tried to do under controlled conditions. At the point where you convince yourself that it works, you've got to go out and change scales and you've got to do a field-scale study. One of the slides I showed was an echogram. In the first part of it, there were a lot of fish. When the high-frequency sound was turned on, there was a dramatic reduction. We repeated that test 17 times. Then we confirmed that there was a strong directional avoidance response and that it was repeatable. Finally, we measured the effect of excluding fish in front of the intake.

And getting to your specific question about how you consider replication, if you're dealing with a test where you are turning the system on and off, the experimental unit is very different than if you're trying to run a system for an extended period of time. And the way we dealt with it was to have a control site and a test site. And we planned to run the system for 90 days. The replicate in this case was the difference between the control site and the test site. And the more days, the greater the number of replicates. The greater the number of replicates, the better your ability to statistically differentiate a chance event versus something that you actually did to the fish. And so the answer depends on what question you're asking. But in a field study, it is important to get a good control site and a good test site.

MR. SCHILT: At least at Russell, and everyone tells me at other places, if you say you want to replicate with units, we have four pump-back units, and we know there's a tremendous difference in fish entrainment at those units. So across four units, they are 80 ft wide, side by side. They're really different, for hydrodynamic or whatever reason; you get more fish in this one than you do in that one. So that's pretty hard to say, we'll use this one for a control. And the other thing I'd ask, and my only experience is at Russell, is how do you count the fish? It's kind of hard. And there are a couple of ways you can do it. One is with hydroacoustics which Gary Weeks mostly deals with at Russell. It's a great technology, but it's imperfect. Or you can do it with nets, and I mostly do that. It's a great technology, but really imperfect. And getting those two kinds of datato mesh is difficult, and never mind if it takes the fish time to go through the system, they don't go through the dam instantly. So if you're turning things off and on, there's going to be some smearing. All of those things are really difficult. And we do the best we can with it.

DR. DUNNING: That's a good point, about differences between control and impact sites, and you don't necessarily have to have a control site that has the same level of impingement, entrainment or diversion as an impact site. The requirements of many of the models that you want, or at least a particular model that you can use, is before/

after control impact pairs type analysis, is that the difference between the control and impact site remains constant throughout your test. So you can start out with a control site that doesn't necessarily have the same number of fish as your impact site, but there is an assumption that the difference remains constant.

I believe we as a group need to be sensitive to the statisticians and the ecologists who have expectations about how you will quantify information and how you will demonstrate the probabilities that things are due to chance or to perturbation. And I'm not sure that's been fully done. It became very apparent to me when we submitted a paper for publication in *North American Journal of Fisheries Management*. We had a very sophisticated reviewer who said you really ought to be doing this before/after control impact pairs analysis. When we did it and resubmitted the manuscript, the reviewer said, there are two major assumptions that you didn't test for that you really should. My first reaction was, quit bothering me. I've got an 87% reduction in impingement and you'are worrying about testing assumptions as to whether or not I've got a difference that's statistical. The fact is, he raised a very good point. I became much more sensitive to people with a different perspective who will impose their rigorous standards on us. If we're not willing to hold up our work to the rigorous standards that are there, we're not going to get a lot of respect and people are not going to pay attention to what we've done. And I think that is pointed out very well in this sentence from the Office of Technology Assessment Report (OTA 1995) which I'm going to read, and Joan Harn should be complimented for it: "Statistical analyses and behavioral responses are often inadequate and thus it is hard to assess the effectiveness of a technique." An issue that often arises is the apparent differences in the ways various investigators have used statistics to interpret data. What may appear to be a positive response in one statistical analysis may appear to be nonsignificant in another. It says to me that, as a group, we need to be very sensitive to the kinds of tests that people consider rigorous. And if you don't want to use those kinds of rigorous tests, we're going to have the same problems that were pointed out here.

DR. NESTLER: I would like to try to throw an umbrella over that question quickly. I would think that the first papers that came out on all of this stuff was just 1993 or 1992, something like that. So there's hardly a track record. In Dennis Dunning's and our analyses, our experimental designs are very similar because we were talking to each other during that whole time. We were also talking to Ned Taft. Consequently, you'll see commonality in approach, and all of these papers are in the literature. Now we're beginning to get a little bit of a track record. So I think we are maybe standardizing to what's acceptable, and reviewers could go back and look at the other papers and say what did and didn't pass muster last time. I see this as a manifestation that this whole area is really in its infancy. I think we are born, but we are still struggling with very good issues like, When can you claim success? That's a very valid issue, and we still have a ways to go.

MS. HARN: When you say "we," who do you mean? Not all of you are publishing your work. A lot of it appears in the gray literature and you know that whole standard of review andthe credibility. Overall, I've heard a lot of claims that we have an effective system in the presentations made here. And I know that there are a lot of skeptical people out there, particularly among the resource agencies, who don't buy it.

MR. PLOSKEY: A lot of people won't buy it even if you publish statistically significant results based on good designs. The problem is in the application of a technology to different sites, most of which present deployment challenges. I'm not sure you will ever apply these technologies without testing them at every location.

DR. TURNPENNY: I want to comment on expectations and the criteria for success. We started work on acoustic deflection systems basically for the nuclear power industry in our country, where they've had recognized problems for 30 years and they're seeking to improve their environmental image. And the nuclear industry has basically said to us, if you can cut down the fish catch by 30%, then we are listening. We did better than that, and so they're very keen on the concept of acoustic deflection. We have other people in the U.K. who are required by law to fit screens as a result of new legislation. So instead of being judged against the status quo, we're then being judged against a 100% efficiency target. Therefore, we find there are two kinds of users: Those driven by their own environmental agenda, signing on to environmental management standards; and those driven by legislation. And because the expectations differ between these two groups, obviously the acceptability of the system will differ.

DR. NESTLER: What do you think the reasonable expectations are, particularly for new technologies?

DR. TURNPENNY: We have been dealing with a particular issue in Northern Ireland where there are a number of small hydro stations being built. The requirement under the law on these new stations is to fit mechanical screens, and developers can apply for an exemption from that, to fit alternative devices that are as effective. The history of the use of mechanical screens is such that there are fish mortalities associated with the screens, possibly because in many cases they have been badly designed or not properly cleaned. And the other factor is one of enforcement. Many of these screens are actually pulled out of place when there's no one looking, and so the effective benefit is nothing near 100%. My own view is that if we can achieve 95% in that situation, then that ought to be at least as good as the mechanical screen.

DR. NESTLER: I've heard valid criticisms of behavioral barriers, i.e., that a physical barrier can at least be designed to very rigorous criteria, based on fish size and velocities based on bulk flows. Do you think we will ever get to such rigorous design criteria for behavioral or acoustic systems?

DR. TURNPENNY: I don't think so, because you've got to think of a normal distribution of fish. And you will never get those fish at the extremes of the distribution to perform, with any parameter you care to measure. You will always have a fish being chased by another fish, and it will do something you don't want to it to do. So you will never get 100%.

MR. MENEZES: You may not get 100%, but the issue of whether or not the stimulus or a signal is effective and how to do the experimental design is only one problem. 1 think we have to come to some agreement so that the people who review this work can accept it. And while I recognize that there may have to be a demonstration at every site before everybody agrees that at that particular site it works, there should be a fundamental difference: at some point in time the demonstration should say, this signal works for this kind of fish. And the second part is that they should go to a particular site and do a test not to determine whether that stimulus is appropriate for that species, but to determine whether the engineering work has been done so that it's an acceptable solution at that particular site. There's a fundamental and important difference there, which I think will have some outcome on what's considered effective and what's considered acceptable.

DR. DUNNING: Another point is that, while engineers are very fond of being able to identify details of physical barriers and to describe them, I think what we've heard over the last two days is that there are people who look at acoustics and can describe acoustic fields with equal detail and glee. My assumption is that there will come a time when somebody will identify the acoustic parameters that should be applied from one site to another, recognizing there may be some site-specific differences. But if somebody says there ought to be a minimum sound-pressure level, then you should be able to measure that in the field as well as model it.

MR. TAFT: I might add that many of the systems being installed outside the Northwest have not proven effective. The money has been spent and they don't work. I know that the criteria here in the Northwest has been 100% protection, and behavioral barriers were verboten. That has changed. There are position papers from the agencies now that say that experimental applications are okay. I guess the idea is to let the technology be evaluated, and not let it be applied 'big time' until it has proven itself. But for most of the hydro plants in the country, much of what is being prescribed by the agencies through the FERC licensing process is not working, and will continue to not work, although a lot of money is being spent. And that money could well be spent on other things, at least to give them a chance. They ultimately may not work, but at least give them a chance. Every time we try to propose something that is not a structural barrier that people can look at and touch, we get the door shut in our face.

DR. COOMBS: As a basic researcher, someone who lives in a kind of myopic world, focusing on lateral-line research in her lab, I have really struggled with these complex large-scale issues that you 're faced with, and you are the ones who are attacking the problems on a large scale and developing the techniques. Now, Art Popper just asked me to come upwith a list of basic research that I think would be helpful to this program. And I would actually like to reverse the question, to ask those of you who have field experience developing these techniques what kind of information you need. That is, tell me what we, as basic researchers, could provide you that would be helpful.

MR. PLOSKEY: I think the stimulus issue is a perfect example of how laboratory science and environmental engineering can complement each other. Work needs to start in the lab by people experienced with protocols for response testing. Once adequate stimuli are identified, biological engineers should test signals at field sites and scales. I've heard conflicting evidence in presentations during the last two days, and I don't know whether I agree with the conclusions of some of the presenters because their results were n ot presented in a statistical framework.

MR. TAFT: Is there any way that we can untether and unchamberize these fish and do these conditioned-response type tests with the fish not contained or held in-place; where you get, say, a heart response while the fish is in a more open environment, maybe even in flowing water? Because the information you have all generated over the years is fascinating, and I never appreciated it until you all presented it. But it didn't dawn on me that all these fish are basically held in a sling for the purpose of just looking for a base conditioned response to, say, frequency.

DR. COOMBS: That's true for a lot of the studies we do, and obviously we like to restrain the fish because then we have a much better idea of the stimulus field when the fish isn't roaming through it. I didn't really have much time to describe the methods that I use in many of my studies, but for the behavioral studies involving the mottled sculpin, the sculpin is basically free roaming. Now, albeit, it's confined in a small tank in a lab, but the animal is free-roaming. So the animal is not restrained, but is free to do what he wants. In fact, we are capitalizing on a naturally occurring behavior that the animal would express in the wild. In fact, sculpin orient towards this chemically-inert vibrating object in the lab, that is, they bite at it as if it were natural prey.

One of the things I would like to do with a colleague in New Zealand is to look more carefully at the involvement of the lateral line in rheotaxis and in entrainment behind obstacles in stream environments. If we were to do these kinds of things on a small scale, with, for example, a flow tube or a flume, and get more information about the kinds of cues that are processed through the lateral-line system that enable these abilities, would that help you out?

DR. BROWN: That's a good piece of it, yes.

DR. NESTLER: Maybe I could rephrase your question for you. Rather than saying, here are the kinds of things that you could do to help us, maybe you could think in terms of upscaling what you're doing to the level that would make it more compatible with the information we need? And I certainly don't expect full-scale evaluations. And I find the net-pen tests that we did are pretty useful and they are 'in between', i.e., you're much closer to prototype scales in a relatively large net scale than you are in a tube or in an aquarium. And therefore anything that you learn would be easier to go upscale two orders of magnitude than it would to go from an aquarium and upscale four orders of magnitude. So I think maybe there is a little room for both ends of the spectrum. We can identify things that would be useful at a fine scale that you might consider, how could you upscale what you do in a laboratory to at least begin approaching, get half way to prototype, a fraction of the way to prototype scales.

MR. MENEZES: One of the things I would like you to consider while you are doing these small-scale lab demonstrations is the general consensus here that we need to focus on lower frequencies. There was quite a bit of discussion about near field and far field. I think we all agree that the lower you go in frequency, the further that near field extends. I have some concern about how we test low-frequency near-field effects in small tanks where reflections become an issue. If the tank is 2 feet long and you have a fish in there and a source in one side, it doesn't take very long for the sound to not only hit the fish but hit the far wall and bounce back. And if I treat it as a detector problem, that initial incident wave overlaps in time or comes very close in time to the reflected wave. And with a good reflector, there won't be a big difference in signal-to-noise ratios, and the fish might react in an echo-free location because of the situation you have him in, and he won't react to anything because the reverberation is killing him. I don't know how you deal with that, but just think about that.

DR. HASTINGS: I have over 10 years' experience doing this in a lab. And if you put a J-13 transducer in a 50-gal tank, and if you are in the nearfield, you don't see the farfield. If you stay in the near-field of that transducer, you are in the nearfield. Propagating sound, even if it does reflect and come back, has such a small particle motion that the contribution is not there. So it's a problem. Then if you're acoustically outside the nearfield, and as you go higher in frequency, without a doubt you get standing waves. One way that you can deal with that, if you want to look for certain things, is to normalize things to acoustic energy density at whatever location you are, although you have to measure the field locally at that point. You can characterize it, but you have to make those local measurements. In my lab we use an active technique to create traveling waves in a wave guide. We put a J-13 at each end, we measure the transfer function between two hydrophones in the wave guide, and then we make that transfer function be one for a traveling wave by controlling the terminating impedance. In other words, we actively create an anechoic termination, down to 12.5 Hz now. So there are ways to overcome this inside the laboratory, but you have to be aware of those waves and you have to think about it.

The other thing I would like to say is that a lot of the signals we've seen that are effective are pulsed or temporal. And if you have a pretty good sized tank, like the ones we've seen, like at the Naval Research Lab, and if the fish is responding to a pulse tone, you usually have time to see the response before you get the reflection. In other words, that's possible. And I know there's some work going on at another lab right now on the mauthner cell response, and they have time to see the fish respond before they ever see reflection off the wall. You just have to do the proper signal analysis. So, yes, you have to be aware, but it's not like you just can't do it. You can do a lot of things.

MR. CLEGG: I'd like to ask a question of the researchers, inasmuch as the fish themselves in the wild have an objective in life. If it's an upstream spawning fish, its objective is to get home and propagate. And therefore it has a behavioral instinct inbuilt in its body. And the downstream migrating smelt also has an objective in life to get out to sea and grow to adulthood. Now, how do you deal in the laboratory with the instinctive behavior that's built into fish?

DR. COOMBS: I can just tell you how we specifically deal with that problem in the context of our behavioral paradigm. As you know, the mottled sculpin has a naturally-occurring unconditioned feeding and orienting response. And one of the things that I didn't tell you yesterday is that to get this behavior and to get it reliably, you actually have to keep the animals food-deprived and you actually have to reinforce them with food after they strike at this aversive bead. Because believe me, if they strike at it a number of times, the response will habituate. So it is important in the lab that we take these things into consideration. And we do take very careful measurements of those conditions that are necessary for maintaining the proper motivation of the fish.

MR. CLEGG: But can you tell me where you're getting these animals that you're using, are you taking them from the hatchery or from the wild?

DR. COOMBS: These are animals collected from the wild in Lake Michigan. And I would just like to make one other comment about how you know you don't have a bunch of scattering when you have the small tank acoustics. In our particular instance, we've got a very small vibrating sphere with a maximum displacement of ~ 3 mm. We very carefully measure the pressure-gradient pattern with both hot-film anemometry and a hydrophone, taking the spatial derivative of pressure to get the pressure-gradient pattern. We then match that to the mathematical predictions. Having done that, we've convinced ourselves that we are getting a nearly ideal field as though it were unbounded.

DR. POPPER: I want to make an observation. I think something you said, John, is really valid, and that is to upscale some of the things we do and bring it to an order of magnitude larger. While doing some of the stuff for Joan Harn for the OTA report (OTA 1995), I had the opportunity to review a lot of the gray literature that some people in this audience have produced. And what disturbed me was that when some people went down to that in-between level, the behavioral analysis was rather weak, from my perception. And they weren't what I would consider unbiased, rigorous, double-blind types of experiments. What I'm suggesting is that we eed to go up, but at the same time we've got to bring in to the experiment the experience of basic scientists in how to ask the question from the standpoint of an unbiased analysis of the results. Because I would argue that some of the results that I saw, and some I know were absolutely incorrect, at least left open to question the validity of the data. And so I think that there's got to be a merger. I don't think it's easy for us to go up two scales of magnitude sometimes. It's hard technically because I have a little lab with 900 square feet. And to do what Ned Taft does, I need a bigger room, so maybe I can do it with Ned, which would be a very productive thing. But at the same time we've got to see how to ask the question so we get our data really valid. Doing a collaboration would be great.

MR. SCHILT: We just built this place at Russell, and John Nestler is really the boss of that. It's certainly not anechoic, but I think it's pretty good. It's made of vinylized canvas, it should be transparent. If I can get rid of phytoplankton, we could see the fish. There would be some things that would be good about it. You skin-in people, you folks who know how animals work inside, it seems that we live in a world of trash racks and huge mountains of water going by way too fast and things like that. And never mind bureaucracies and things. A fish can only pay attention to so much at a time, just like the rest of us. I've got this notion that if you nudge an anchovy on the side with a velocity of water, it would almost have to turn right, because they do that day in and day out in their schools. If there are ecological equivalents of knee-jerk reactions – those things that the fish might not have very many options about – those could be very, very useful.

DR. POPPER: Which basically says, take advantage of the natural behavior of animals. And that's something we try to do. Sometimes while we've looked at an animal, it's doing something under certain circumstances, and you condition the animal to do that more often. That's what Sheryl's doing, and that's one way to go.

DR. SCHRECK: It seems like what we're really getting at is this business of experimental design. And I guess I really appreciated Neal Brown's description of the predator relationship with prey. I guess I would add genetic state as the third vector, and the fourth would be something like the state of the organism, e.g., is it at rest, is it active, is it stressed, is it healthy, is it sick? And I think in so many of the experiments that we do, the researcher has to be aware that we're dealing with an animal that we're asking to behave in an unnatural way. That's the best you can do, but you just have to be aware of it. And then you put that within some context that you can use. I think there's a lot of danger, for example, in using the same organism over and over again in many of these behavioral tests, because they learn quickly what's comfy, what's not comfy. I think as long as you're aware of it, it's okay, because then you can account for it and design subsequent studies to address that.

MR. CLEGG: In the experiments we did in our open-sea cage, when we were herding and driving the fish, it was obvious that there would be an element of stress in there since we were driving them in only one direction, but we gave them an alternative way to go. But after each test, we deliberately gave them the freedom of the sea cage again and fed them, and in some instances we would leave them for up to two days before we tested again. Now, we would also put divers into the cage sometimes to see if there were any dead fish at the bottom. And if there were, then we would know that we were doing damage. We were also looking at fish to see if their scales and other things were being damaged. But for us to know whether or not at one test stage we are putting them through too much stress, whether or not it is relevant, is quite a difficult question. But we figure that leaving them for two days after one half-hour test was enough for them to get over the stress. And we just observed their behavior to see if they were happy. If they were all sitting at the bottom of the cage sulking, then we figured we had done too much damage to them in our test. But if they were running about happy and merry, then we assumed they had got over the stress and we could go again.

DR. SCHRECK: It depends on how you determine whether they are happy.

MR. CLEGG: I generally look upon it, if they are feeding, then they are happy. Maybe that's not right. But if hey are taking food, they seem to be okay, ready to go again.

DR. SCHRECK: I can tell you that very brief periods of stress can have long-term, meaning weeks, consequences on learning ability and that sort of thing. So I think it's all graded. I think it would be useful to ask Frank Knudsen what he thinks in terms of how much acclimation time is needed before you set up an experiment.

DR. KNUDSEN: When we did our experiments, we had two loudspeakers at each end. We measured heart rate, of course, and I know from modern experiments that heart rate is a good indicator of stress. When we introduced the fish into these tubes, the heart rate could be as many as 90 beats per minute; within the first 24 hours, it was down to 40. If you left the fish there maybe for a week, it could be down to 20. And we knew when we introduced the fish into the experimental tube that if you are immediately running experiments on it when it has a very high heart rate, it doesn't respond to it at all. So it is obviously very, very important to give the animal a very long acclimation period.

MR. SCHILT: There is an assay with blueback herring, that is, if they die, you figure they're stressed. And it seems like that when we put bluebacks in there and a bunch of them die the first day and a bunch of them die the second day, and not as big a bunch of them die the third day, and after the third day, they mostly don't die anymore.

DR. BROWN: Is that before you stress them?

MR. SCHILT: That's before you stress them at all. But those are bluebacks. The anchovies are just as bad.

MR. NOVAKOVIC: Everybody here is talking about the people like me who are developing systems to guide fish. And different companies have different ideas of signals and infrasound, and I've heard some people say that the only thing that will work is 10 Hz, other people will say it works at 600 Hz or whatever. And also we've heard from the scientists who talk about the ability of the fish to hear, to interpret. That's all great. But I haven't heard any questions or comments from the federal and state agencies that control the ultimate acceptance or non-acceptances of these systems: where they stand, their willingness to have an open mind, the differences between regions and between states, differences between a regional director's attitude and his assistant's. These are the people who ultimately will govern whether or not we are allowed to do something in South Carolina or Oregon. They are the key players in getting the science of fish guidance with sound, which is what this workshop's all about, accepted and moving forward. It almost makes me feel that certain things need to be standardized. For instance, maybe we need to have the American Association of Fish Guiders, or something like that, set some standards and act as an official body in dealing with these agencies and getting them to come onboard. We can't do everything on our own, because ultimately one guy can put a stop to any installation that he wants to. This is what I hear over and over again from all the actual and potential operators. So I think that maybe the scientists who understand morphology and other aspects of fish hearing need to work as a body with those of us who are trying to promote different technologies, and then put it all together.

MR. TAFT: I think the agencies are basically a reactive group. They're basically all from Missouri. And I think the burden of proof is on us. If we aren't convincing them, then we aren't doing a good enough job. Some of you who know me are probably wondering why I'm saying this. I'm usually on the fence or more on the other side. But it is true, the agencies are loosening up. As I said before, there are position papers coming out, one in California, one in Washington, I believe, talking about behavioral systems, at least they acknowledge that they exist. In years past, I have had agencies who would not even let me mention behavioral systems in reports. And now the burden of proof is really on us to show that these things work. And I don't blame them. There's been a lot of bad stuff done over the years that's caused behavioral barriers to go in and out of favor since the '50s. There were light and sound studies done back in the '50s. There has been a crescendo of research activity; one person is successful with a behavioral device, nobody can replicate the results, and the device goes away for a while. If we're going to prevent that from happening again, we need to put all our heads together and figure out how to do this. And I think this is about the earliest that I've ever seen a group as diversified as this come together on a problem. It should have happened five years ago. But as you said, the baby's born; it's still an infant, but at least it's born. So I'm encouraged by that. I think we're going to have to show the agencies, and in some cases I don't blame them for the stand they take, based on some of the information they've been asked to accept.

DR. FAY: I think part of this question is just accumulated credibility or something. And it is probably not my place to say this, but there's a wonderful forum to start with, a more or less neutral and scientific forum to start paying attention to and presenting yourselves and your results. The Acoustical Society of America has a new technical committee on "Animal Bioacoustics." And many people in that group are extremely interested in this; they are very receptive. They meet twice a year, have an archival journal, and hold meetings and publish a lot of abstracts, and the whole group is full of the best in the field. It's a place where you can become known, where your ideas can propagate, and where this whole effort's credibility can be increased, I think.

DR. NESTLER: From my perspective, this whole paradigm is really two things. The short-sighted answer is that we can build something and clamp it onto a trash rack, turn it on, it scares fish, and we feel good. But much more fundamentally, we need to build a knowledge base of how fish respond to the two variables, i.e., the hydraulic and acoustic regimes, that are most impacted by the Corps of Engineers and other developers. Oftentimes we might apply something at Dam A and somehow or other it actually works, and then we go to Dam B and it doesn't work. We have no idea why because there's no knowledge base that we supplemented in the first activity. We didn't develop something from the ground up so that we could take that knowledge to the next application. I like your comment about the Acoustical Society of America because it gives us the opportunity to build a knowledge base and it's also a good interface for us to meet in the middle.

DR. DUNNING: I'm going to go back to the OTA report and quote it again, because I believe it reflects perceptions about the work that's been done in this field. And it says "often research is not described in such detail to allow a thorough analysis of the results. Thus it becomes difficult, if not impossible, to assess the effectiveness of many of the techniques described or the results reported. Some experimental results seem at odds with others and care must be taken in interpreting this information and conclusions reached should be viewed as tentative." Having read that, if you were a resource **agency** person, I suspect you would be very careful about what you committed yourself to, recognizing that you don't generally win points in a resource agency by taking a new position. I believe there are some very constructive comments here, including that you need to describe in sufficient detail what you did so that somebody can go back and replicate it. I believe the problem that we've had in acoustics is this patchwork of success and lack of success. When you have a success, there's no doubt about the fact **that** it works. The problem is when you don't have success: is it because you don't have the right signal, is it because you don't have the right sampling design, is it because you have unresponsive fish because they're unhealthy or they're in a state that they're simply **not** going to react? Is the system you're installing simply poorly designed? Or have you picked the wrong location to put it in? I believe as people who are in this field, we need to keep these ideas in mind and recognize that the resource agencies are skeptical for a very good reason, and there are some practical things that can be done to try and address those concerns. It's not simply putting your arm around somebody and saying, let's be reasonable, you know, it works. It's going to take a lot more than that. It's going to take some of the things that have been pointed out. I don't **have** stock in OTA, but if you haven't read this report, you ought to read it. It really is an eye opener. Because **when** you're on **the** side of developing these things, you say to yourself, I don't understand why resource agencies won‘t listen. Well, read it, and you will understand why.

MR. MENEZES: I don’t disagree with the regulators, and certainly if you are in an agency position, going out on a limb is not necessarily a popular thing to do. But we do have some other situations where, for instance, we did something at a hydro facility in New England, and when the regulators saw the infamous popcorn video, there were no ‘ifs, ands or buts’, the fish were taking the next bus out of town, and we were doing something. Then when it came time for discussion of what to do the following year, it didn’t gravitate to putting that in and solving the American shad problem, it went back to what they felt more comfortable with. And they felt more comfortable with steel and concrete, even though it was more expensive and even though different people on both sides had different opinions. But certainly nobody was holding their breath with high expectations that the concrete and steel approach was going to work. So there is that problem with regulatory agencies, i.e., when they’re faced with compelling evidence, getting them to pony up and say, yes, that’s it, let’s get on with it.

MR. **TAFT:** That work was done in “91 or ‘92, I believe. And three or four years later, I don’t think there was an acoustic system of that kind in operation at any of those hydro plants. There was a reason for that. I saw the video. I was there when the fish were jumping. It was really impressive. But they still aren’t convinced.

MR. MEYER: Ed Meyer with the National Marine Fisheries Service. I think you hit the nail on the head in your discussion, because I’m a skeptic of acoustic behavioral barriers. I’ve worked with screens. Screens are physical barriers. I know I can design them. I’m an engineer and I can design screens, and they are effective in protecting fish. Resource agencies have to be conservative. Acoustic technology, behavioral technology has a bad track record. Specifically, what seems to work at one site or location is a total flop somewhere else, and nobody knows why. So there’s no way that any resource agency is going to accept that when their responsibility is to protect the resource. They’re not going to take that chance. And I don’t think any of you would, if the position were reversed. If your responsibility is to the fish or to the environment, we have to be on a conservative track.

MR. MENEZES: Yes, but I think there are several important points. The first one was in Vernon’s situation where we weren’t asking anybody to take the results from Vernon and apply them to a second site. The issue was always Vernon, and it never deviated. The second point is that there was no evidence to suggest at Vernon that putting in those fish screens in concrete diverters would guarantee success either.

MR. TAFT: They ended up putting in a louver system.

MR. MEYER: Well, I’m not big on louver systems either. Louver systems have a track record right down there in guidance efficiency. Sometimes they’re great, most of the time they’re not. And even with acoustic systems on a year-to-year basis, we see wide fluctuations in passage efficiencies. I have heard numbers thrown out, 85%, 75% passage efficiency, but there’s always the caveat, that’s the high. What’s your range? 45% to 75%? I know with a properly designed screen facility, I can get 100% and mortality will be next to zero.

MR. **TAFT:** But in reality, Ed, a lot of the screens haven't performed well either, and that's why we're looking at extended screens and all of that kind of stuff. I think the three panel groups are all generally promoting the concept of pursuing research on fish-protection systems on a smaller scale before going into the big scale, based on past failures. There's a lot of pressure on people like us to produce results; the engineers and managers want results, and they want them now. And so there's a lot of pressure to go right to the full scale, and it's a mistake. I think you're seeing a lot of agreement here, based on past experience.

MR. MEYER: And I agree. The Columbia is a tough system to work in, and the traveling screens have their faults. I'm not saying that those are a shining example. It's just that when you get into a controlled, controllable situation, say, up to 2000 or 3000 cfs diversions or smaller scale, we tend to be on the conservative side, and those happen to be physical screens. It's overcoming your history, the history of behavioral barriers. One other thing: when you were talking about stimuli, I think you're on the right approach there, with species and stimuli. And I would also say life stage, because I would venture to guess that a newly emergent fry does not interpret sounds or stimuli the same as a smolt or smoltified salmonid heading downstream. Certainly his capabilities to react to that stimulus in a flow field is not the same; it's the difference between a fry 25 and 30 mm long and a smolt 80 or 120 mm long. They have different swimming capabilities. If you put a fry out there and ask him to be guided downstream, he may give up the ghost and go right through your sound system. So you have to look at it in those terms.

DR. DUNNING: I'd like to address the point that you made about the track record for behavioral systems. It's a valid point. I believe we need to recognize the difference between a technology demonstration and the application of a technology at a particular site. In the case of alewives and high-frequency sound, for instance, I think we've even convinced skeptics like Art Popper that it works, for whatever reason. The fact that it may not work at any number of sites could very well be due to misapplication of the technology. You could design the system wrong, you could be putting it in the wrong place, there are many things. It's really easy to screw up an application.

My last point has to do with resource agencies. 1 deal with a conservative resource agency, the New York State Department of Environmental Conservation. And we told them that conventional methods don't save alewives very well, 35% is the typical recovery rate for live fish off a state-of-the-art screen. All we asked them to do was to consider looking at behavioral systems. We didn't say 'buy in.' We just said, give us the opportunity. If we can't demonstrate to your satisfaction that it works, then we'll do it your way. That worked extremely effectively. We knew what we wanted to measure, we knew what our target was, and we worked with the agency on a regular basis. And by the time we were done, they said, it's the best technology available under the Clean Water Act, go install it.

DR. NESTLER: We keep discussing this from the extreme viewpoints, like it's screens versus sound. My perception is that if you have water going through a screen, it's making sound. Water going through a dam is making sound. We're inadvertently guiding fish now with dams. And it gets back to that knowledge-base issue and understanding what fish do. I hope the emerging paradigm will be to make screens more efficient by viewing them as hydromechanical sources. I don't see this as being necessarily a conflict between one technology and another. I see this link called the octavolateralis system, the system that the fish uses to respond to flow and to sound. You have that problem when you design screens, how do fish respond to flow? And you may not know it, but these fish are dealing more with the purely sound aspect of flow. There is a commonality there, and I don't want us to get hung up on 'us' and 'them'. It doesn't have to be.

MR. MEYER: I agree. There are many similarities between screens and sound. And your approach to New York State was to say, your screens can only do so much. If we turn that around, we can do better than that, will you accept? We turn that around, as Ned has pointed out. We have adopted experimental screening criteria here in the Northwest, and it says basically, we'll allow you to do experimental screening, but it has to meet what a conventionally designed physical barrier would meet.

MR. BROWN: I agree. We have to remember from an agency standpoint, or from anybody's standpoint, for example, generic terms. In our field, people continue to refer to strobe lights. Now, are these the strobe lights that were utilized five or six years ago? If they are, they are not relevant to what is available today. The technological climate and the quantum leap that has occurred in strobe lighting is like comparing a Piper Cub and a stealth bomber. So if you're prejudiced1 towards strobe lights, or **any** other type of behavioral behavior, because of historics, you might not be well grounded in what you're talking about. But if you don't have the opportunity to have these tested, then you've got a problem; you might be missing the boat.

MR. TAFT: I'd like to say something that's been said before, just to tie this up. I agree, we shouldn't be comparing; we should be combining. I think we could use sound, lights, any of these things to improve efficiencies of poor systems or as a first line of defense or whatever. And the relative cost of a behavioral system is nothing compared to structural systems.

MR. BROWN: And I agree with what Ed Meyer is saying. You know, I think John Menezes said it yesterday, when he started talking about this elegant forging of various types of barriers, whether they be physical or combinations of behavioral barriers.

DR. POPPER: I started thinking about this whole question of ontogeny. I think that's something we really need to keep in mind, and Ed Meyer pointed that out well. I remember looking at the material from OTA and one of the reports about the use of light. And **what** happened was that if you use a light to control a fish, these are laboratory experiments, as the animal got older, its response to light would change. And it may be that particular light or sound or electrical-field effects may work on a fish of one size or one age-class, and then a week later, the anima's response totally changes. Actually, you **can** see this is true not only for fish but for all animals. Behavior is what the animal does at a certain time in its life that's important to it. It may change how it responds to things as it gets older. So it's not just that we can worry about what happens with a 2-inch-long animal, but what happens when it gets to be 4, 6, 8 inches long. That's a big problem, and we've got to worry about it. So it is not only species to species, but within-species parameters.

MR. TAFT: I would add to that, hatchery versus wild fish.

DR. POPPER: Oh, absolutely.

MR. MEYER: Getting back to the development of what's passed and the strobe light and whatnot, and this is from my viewpoint. If you get a failure in a behavioral barrier, it fails at a site, certainly somebody comes along 2 years later and said, we've done it better, we've upped the frequency, we've got wider light-shining apparatus, it's better now. And I'm afraid many of the agencies just have a bad taste in their mouth where somebody says, oh, they were using the wrong wave length at this, we're going to try a different sound or we're modulating it differently, and we have the same results. And it may be just the difficulty of working at a particular site. But, I tell you, that's where a lot of people in the agencies are coming from. They've been burned on these sort of things, and they don't see any consistent work --

MR. PLOSKEY: I would just like to interject. We should consider sound to be an enhancement rather than a replacement for present methods such as screens. A method does not have to be 100% effective to be valuable. Suppose you had an acoustic technology that was only 50% effective overall because it did not work well under certain environmental conditions. Wouldn't it be valuable if it increased project passage by 10-50%? I hear of the agencies hoping for a 5% increase in fish-guidance efficiency at Bonneville, particularly at night. What if you could use an acoustic technology and increase FGE by 25%? So 25% looks pretty good, and 50% would be wonderful. Whatever the effectiveness, it's the incremental improvement we hope to achieve.

MR. MEYER: I think Gene's right. Augmenting physical barriers is probably right now the best application for behavioral barriers and such. The problem I get faced with is when you have somebody who wants to use it solely because it's cheaper. It may not be better for the site, but he's got it in his mind and some salesman has pitched it to him that this is going to solve his problems. And invariably he spends the money, it doesn't work, we're right back at stage one, now he's in the hole and we could have used the funds for a physical screen or something that we knew was going to work in the first place, and he's out that much more.

MR. DACH: I'm Bob Dach with the Army Corps of Engineers. With all of these systems, I think the problem that we run into is the end user and the people who art footing the bill for all of this. We have projects out there that have absolutely no protection at all, and we're faced with having to go with something that we know might work a little bit versus something that we're not sure will work at all. We don't have an unlimited supply of money, though it's quite a lot of money, granted. When it comes down to it, what we will do and what we inevitably have always done in the past, is go with what we know works even though it doesn't work well. And then after we put that money up, we go back and look at it and see if there's any way we can change it or make it better.

The problem that we're running into now is that there are folks asking, why are you doing screens when we have these sound barriers that you can use? And the resource agencies are saying, because we don't know that the sound works. And what we're saying is that they may very well work together, but we sure as heck don't have the money to pay for them both. So where are we right now? We're at that point in time where we take what we have in hand, and we keep funneling a little money into the research arena, and hope that that new technology comes along, so that we can apply it to the systems that we are constructing. I think everybody is right that we have to use both of them in conjunction with each other, but we have to go with the one that's going to work the best first.

DR. NESTLER: That's risk management.

MR. TAFT: I think the way this all may flesh-out eventually is that light and sound, all of those things, will be used as a supplemental measure. And through that process, we will learn about them, about how to orient them, how to operate them. And that will bring credence to them, and maybe in the future they will be applied as a singular protection. But I think that's probably the intermediate path that ought to be taken to bring these things out.

DR. NESTLER: It's really an issue of risk management, and what's happening is that it's the sponsor and the resource agencies that are taking on all the risk right now. Vendors tend to get paid whether the system works or not. So the people who really shouldn't are being asked to take on the risk.

MR. BROWN: I take exception to that. Our approach to the market is that we understand the down-side risk of a perceived failure. Therefore, it's a self-regulating type of approach, because we are going to be conservative in what we promote as a solution. So we're taking the risk every time we incrementally move it out. Yes, we get paid, possibly, but do we get a total return on all the investment w've put into this project? Possibly not. And the higher the risk, the higher the return.

DR. NESTLER: I'm saying that if you put the same onus on the behavioral barriers as you do on physical barriers – say, we won't pay you unless they are 70% or 50% efficient. That's the transfer of risk, and I'm not sure the state-of-the-art in behavioral --

MR. BROWN: I was in California Monday, at a place where we have an application. And I told the people there that we will put it in free of charge, we will run it for a certain period of time at no risk to them, and then we will pull it out if they're not happy.

DR. NESTLER: Other than Ron Brown --

MR. BROWN: And that couldn't be done because the budget horizon is 3 Years in the future, so they couldn't make a decision even if they wanted to.

MR. TAFT: Could we take you up on your offer?

MR. BROWN: I am here, and I look at it from a business as well as a scientific perspective. Let's talk.

MR. MEYER: My comment is that, in my personal experience with the agencies, I have not found them to be unreasonable. They are more than willing to let us try these things provided we are not letting the mainline ‘big ticket’ items slip because we’re spending money on something else. If we can indeed continue with our programming and try to incorporate this into it, we have found them to be rather reasonable about it. It’s when we present them with the either/or situation that we run into a conflict. And that will inevitably hang us up. So to promote the systems as a replacement, or we need to put the money here because it’s going to do better than there, I don’t think is the right approach. I think the only way this thing will make its mark is to show you how it actually can be used in conjunction with existing systems that we have out there.

DR. TURNPENNY: I would like to think that we can learn some lessons from this workshop. Acoustic guidance, from the comments made here, has a checkered history which stems, I think, from a lack of scientific understanding, from a lack of rigor, and from perhaps a hurried pace to meet the high demand for behavioral systems. We heard during the workshop about the various factors involved in design of the system, e.g., fish audiology, signal development, design of the acoustic field, acoustic measurement around the site, statistical design of the testing of the scheme. And I think there are fairly concrete measures that could be taken on all of those. And it would be good to see something from this workshop that would draw together all these different aspects of the program, so that we can go on from here, learning from the failures of the past.

One area that I think is particularly in need of careful thought is what I term the ‘deflection concept’. That is, you get the signal right and you get the acoustic field right, you design your test right and so on, but you must also be sure that you have a valid overall concept for guiding the fish. In other words, you know where the fish are coming from, their depth, their behavior relative to the flow, and where you want to get them. You must analyze all the various parameters associated with that, including their ability to cope with velocities, and so on. I think one must have a cohesive model of what is expected of the fish and be able to answer all the questions relating to that. Is it realistic to expect the fish to do what you’re asking it to do? I think we’ve come a long way in signal design and acoustic field design, but I think the most difficult part is actually coming up with a conceptual model of what you’re expecting the fish to do.

MR. TAFT: This gets back to what I was saying before, about giving the fish more freedom. Despite everything we know, we haven’t done the directionality part of it in an open environment. And then you said something about the Mauthner cells possibly being the initial stimulus. What we’ve seen got me wondering if we were supplying the stimulus that bypassed the knee-jerk response. They knew they didn’t like it, but we hadn’t given them – in the one species, anyway – that initial directionality that they needed. I think that’s what I was getting at in terms of there being anything that could be done to define the directionality, where you could actually see the fish move, rather than measuring some type of potential that’s coming out of the fish, restrained.

MR. CLEGG: Let me put a commercial hat on here. One of the things about being a commercial company is that when you’re involved in this R&D work and you’re involved in it over a number of years and you’ve spent upwards of three-quarters of a million dollars on this sort of technology, you’ve got to ask yourself at the end of the day whether you’re going to be able to sell the product. This is what the commercial end of it is all about, at the end of the day. And when we can all sit around and we can all have good fun doing all of this work in our laboratories and out in the field tests and coming up with the tests, but what we need as a commercial company is comfort from the end users is, yes, if you get it right, yes, we are going to buy it. Now, if that statement is made by the end users, then companies like mine will continue supporting and putting money into R & D to try to get it right. And at the moment what I would ike to hear one of the end users say is yes, guys, if you get it right, we'll buy it. Is that a fair statement?

DR. NESTLER: An 'end user'. Let the 'end user' speak.

MR. PAULSON: Michael Paulson. If it works, we'll buy it. We have spent billions of dollars on plenty of things that haven't worked. I think that we do have an open mind about any sort of device. I think the problem with the Columbia is that it's the most complex system in the world. You're talking different species, different types of dams, different types of water flow. The idea that any one system is going to fix any one problem there is ludicrous. But as far as willingness to buy, I think the agencies do have an open mind. We have bought moving screens, extended screens, baffles, surface collectors, bypass collectors. We're willing to buy damn near anything, if it works.

DR. BROWN: Are you willing to make a commitment --

MR. PAULSON: Today?

DR. BROWN: --beyond buying a system that works, to finding out why a system doesn't work?

MR. PAULSON: Yes. I think right now, we are willing to fund research, if possible. We're not willing to buy at this point because no one has proven to us that it can work.

DR. BROWN: Okay. But Ed Meyer mentioned systems that work over here but don't work over there. Andrew Tumpenny was the only one I've heard mention something that failed drastically; they killed more fish than without the system. He's the only one who mentioned a defeat. Why? It's most important to find the source of failure, more important, perhaps, than designing the system in the first place.

MR. PAULSON: For instance, I was just briefed on the study done at Bonneville, and I think the reason it failed was because it was put in the wrong place. It may very well have worked, but I think for certain circumstances, it was in the wrong place.

DR. BROWN: Did anybody try to prove that?

MR. PAULSON: No. They didn't try to prove it, but they all mentioned that as being a problem.

DR. BROWN: But the job isn't finished, so to speak, unless -- It's like a Boeing 757 crashes and all these people are killed, and so we're not going to buy any more 757s. But that isn't what the FAA tells us. It figures out why it crashed, and how come that doesn't go along with our paradigm?

MR. PAULSON: We have funded studies throughout the '80s for various types of deterrent devices. I think that we still have an open mind. But to buy it, it has to be proven to work. And so far it has not. And that's up to the commercial side there, if they want to sell the product, to figure out why it doesn't work.

MR. CLEGG: Are you saying we have to make it 100% effective?

MR. PAULSON: I think that's an argument that's been raised here, what is 100% effective? Is it 20% effective all the time? That's 100% effectiveness to me.

MR. CLEGG: So you would still buy it?

MR. PAULSON: When you figure that you have bypass efficiencies of 8%, sure.

MR. CLEGG: Thank you. Your name and your company?

MS. HARN: In my work on the OTA study, we dealt with a lot of resource agencies. And the information we got from them was that they're much more willing and open to trying new things at sites where there are no conventional alternatives. And that seems to be the experience that Dennis Dunning ran into at Fitzpatrick, it's the experience that Paul ran into at Georgiana Slough, and it's the experience that you have with the Columbia River – that nothing else works. But why does nothing else work? Is it because those are the biggest, most complex kinds of systems out there? And your challenge is, do you have to develop your system to work at these most difficult sites? And because you don't have the willingness of the agencies to use you as an alternative to the sites that are more simple where the conventional measures are available. And so, given that you're being asked to develop your system at the most complex sites, what kind of research do you have to do, or do you need to scale down? Does it make sense to be scaling down? You know, is there work that can be done at the laboratory level?

DR. NESTLER: That's exactly why Tom asked some of these folks to come to this workshop. Because we realized that was a problem.

MR. NOVAKOVIC: I don't know that there is a way today for any company to evaluate the size of this market. True, the problem is immense, just right here in the Columbia River. The first time I came out here was a year ago, I've looked at it and talked to a lot of people. What kind of studies have been done? What about rotating screens, and this and that? I took a survey of ten people and asked them how much they thought has been spent over the years onstudies and different things to improve fish passage in the Columbia. And the numbers that were thrown at me were staggering. The ten people all agreed on something between $500 million and $1 billion over the last 20 years. Now, 1 have no way to verify it. But looking at that, one would think that here's an enormous market, there's room for 50 companies, if you can resolve something over the next 20 years.

But the problem is that to define a market, you hire a market research company. And I've done that, and they came back with no answer at all. And these are professionals They have no answer because they claim there are too many ifs, if's, and if's. They talked to all these different people and they came back with a market analysis that is meaningless. So when you talk about the risk factor, it's one thing to be employed and know that you're getting paid, even if it's a minimal salary, but it's another thing to take stockholders' money and invest it in something when you can't even tell what the market is. Billions are being invested in the pharmaceutical field and bioengineering. But they evaluate the market by hiring market analysts who will tell them, if you can come close to a solution of this particular problem, you've got a $500 million market. I don't see anyone able to determine that here. In fact, I've heard about installations where people have done alternatives to screens, but I haven't heard of any installations on the Columbia River, other than the the rotating screens that I've been told cost over $100 million dollars. Yet when it comes to acoustics, people get scared. If you ever mention anything like $100 million dollars, or even $1 million, they literally getscared. But they don't think anything about spending $15 million dollars on one simple demonstration of a surface collector.

So I think the risk factor has to be acknowledged. Any company and bank will back you in a risk if you can demonstrate that you are on a path toward that happy day when the bottom line is positive.

MR. TAFT: In terms of risk, I think the reason that market researchers are unable to find or define a market is because the agencies have mixed feelings. This is partly because the negative results have never been reported. I agree with Neal Brown that negative results can tell you more than positive results and help other people who are trying to go through the same thing to figure out what they did wrong. I know in all our EPRI studies that we always reported everything, whether it was positive or negative. But I think that's important, and this sound stuff and this commercial thing that we're in now is totally new to me. In the past we've always contracted this stuff, and all you get is the positive viewpoint. We were watch-dogging, seeing all the studies that were being done and we and the agencies knew all the negative results, but all they hear from the people out to make money is the positive stuff. That's got to leave them with a some doubt. If you get a negative result, bring it up, get it out, and explain why it was negative, if you can. Maybe you can't. I really think that the learning curve has been flattened greatly by presenting only the positive.

MR. MEYER: I want to thank Andrew Tumpenny for presenting a failure. Seldom in the literature do you find failures. At least it should be acknowledged that it didn't work, that the results were not what they wanted, and give some possible reasons why it didn't work. Most people just try to hide their failures and go on to bigger and better things.

A quick suggestion: When you are designing acoustic barriers, I would suggest you take a page from conventional screen design, work with the fish, work with the hydraulics of the system. We've learned years back that you don't set physical screens perpendicular to the flow. Fish come down, they have nowhere to go, and you expect them to through a tiny bypass out the side. They don't find that, they roll over, go over the screen, it's a failure. Current design, we have timing of the fish coming down the screens, we have intermediate bypasses, we know at what point small fish exhaust their physical capabilities of swimming, and they hopefully find those intermediate bypasses. We control the hydraulics in there and guide them to a bypass. I think that's what a lot of the acoustic or any behavioral barrier studies lack. They stick these devices right in the middle of the canal and expect the fish just to hold up at the upper end. They don't give them an option to go anywhere. A fish that wants to go downriver will either tire out in front of it and go through it, or he'll just give up. And I've seen that in some tests that have been done. It's a good way of setting yourself up to fail, because you will fail. And that's what we've found out with the screens. So take a page from the books of the screen designers and set it up that way.

DR. TURNPENNY: That's exactly what I had in mind, working with the overall design concepts, knowing what you're expecting of the fish. I come from a fish-screen speed and screen-design background. So that's my approach exactly.

MR. MEYER: I was just asked how long I have been working on screens. Five years in this area and about three years at Waterways Experiment Station. I've done some Master's work at Washington State University as a fish passage. So total, maybe 7-10 years.

MR. WEEKS: I'm Gary Weeks with Trotters Shoals Limnological Research Facility. The gap I see here is between the commercial people who are trying to do applied stuff in large systems and the scientific community who's doing a lot of stuff on a smaller scale, which is a lot less expensive. But when you move up to a bigger system, to a whole-system experiment or application, the cost increases dramatically and there is great pressure to make this work. And I find it amazing that these people have the nerve to take this kind of risk, because I know in our case, at Russell, there's a lot of pressure to make this thing work. And we don't have much latitude on design and experimentation.

And so the real question seems to be, who's going to fund the development at that scale? And I don't see any of the resource agencies raising their hands and saying, we'll give you a couple million dollars a year to work out these problems. What they want is results, and I can understand that. But it seems right now that the gap between the resource agencies and the application of these systems is in this large-scale experimentation, where the work really needs to be done at each specific site. I'd be really surprised, even if you do the modeling, if you get it exactly right the first time. And I know that your funding is often set for a year, and the expectations are great. And there's this gap between what you can do and what you're planning to do and the results that you'reexpecting to get.

DR. SCHRECK: I think in trying to understand some of the resource agencies, and I rub shoulders with them, is that they would be willing to leap at anything that looks positive. But it's comparable to having a machine shop associated with your firm where you're fabricating these structures, and then somebody tries to sell you a new tool. How convinced would you have to be to invest in that new product? That's sort of where I think the resource agencies are coming from. I would offer something that we haven't really spoken about, the really small-scale applications, of which there are huge numbers. For example, in one county in Oregon there are 40,000 different water withdrawals, each of which require some sort of fish protection. We can be dealing with the end of a pipe to a small canal to a small dam. So perhaps the total dollars for small structures, spread across the arid west, are as great as for the Columbia River. I suspect the east is very comparable.

DR. BROWN: This is a good point. There is a huge market there that would drive this, and I take issue with Paul Novakovic's comment that you can't get a market survey. I did one in about 15 minutes at a public library with a book that came out of the Department of Energy summarizing all the power stations in the United States. I just looked at their summary charts and determined, on the basis of a few assumptions, that there were approximately 10 million ft^2 of hydroelectric intake in this country alone. At 200 ft^2 a pop for a protection device, that comes to about 5000 units.

DR. SCHRECK: And that quantity might actually be smaller if you compare irrigation intakes.

MR. MENEZES: I would like to follow-up on the small-scale systems. We did that, and certainly I'm happy getting on base. I don't have to hit a home run every time. So, between that and then balancing our work, it would work to our advantage. But one of the problems you run into is, while you may have a solution for the small guy, the small guy won't buy that solution until he sees the big guy using it and happy with it. How many small guys do you want to see leading the charge on something? And so you get into this Catch-22.

DR. POPPER: I have a question that was brought up about Bonneville. I was out here in May, and Paul Novakovic and I talked about the project at Bonneville. I know Gene Ploskey was involved in the evaluation. Could you give us a sense of what the results were, maybe some background also?

MR. PLOSKEY: Yes, I can. It was a case of an experiment placed in the wrong location, or a barrier in the wrong location. Not just an experimental screw-up necessarily, maybe a political screw-up. We were going to do this experiment at The Dalles. We were booted out of there and rewrote the plan for the spillway at Bonneville. But that was unacceptable to the agencies, so we ended up at Powerhouse I at Bonneville. We were running out of time and had to decide to proceed or to abandon the experiment in 1995. We may have overlooked some hydraulic patterns that compromised the experiment. I'm proud of the statistical design. We had adequate power in the test to reject a false null hypothesis. Nevertheless, we could not reject the null hypothesis, and we are not absolutely certain why. We were asking smolts to move offshore at Bradford Island and away from two turbine units. Flow was not at a steep angle to the upstream end of this 400-ft-long array of low-frequency transducers. It was largely parallel to the array until it reached the face of the dam where it moved laterallv across the arrav.

Paul Novakovic, Paul Loeffelman, and I stood on the deck and looked at surface flow patterns, and they expressed concern that lateral flows crossing the array at a sharp angle near the dam might sweep smolts across the transducer arrav. I asked them to pick the pier to which they wanted to anchor the downstream end-of the array. We discussed whether we should try to guide smolts past one or two turbine units. But there was no option to cancel the tests. Paul had only one way to receive payment, and that was to proceed with the 1995 test..

I could see the advantage of having an oversight or peer-review committee going into these experiments, some group to provide leverage to the planning process. We should have been there weeks ahead of time and examined flow patterns and fish movements, but that was not possible. Although we had a powerful experimental design, we failed to detect a significant difference between sound-on and sound-off treatments. We proved only that it did not work at that location. We have no inference for other locations or flow patterns. If flow had crossed the downstream 10% of the array at 20" instead of 70°, results might have been different. There is no way to know.

DR. POPPER: Knowing what you know now, would you go back and redesign it and potentially get it to work next year?

MR. PLOSKEY: This is the classic 20-20 hindsight question. I think we could be much more confident in our results. I would spend a lot of time just watching fish movements before the array was deployed. I would want to determine whether fish move with the lateral flows that crossed the most downstream end of the array. Unfortunately, there is a problem with schedules within the Corps of Engineers, probably with any major construction agency. Schedules are not supposed to slip. If I had it to do over again, I would have said that we should not conduct the Bonneville experiment in 1995. Some kind of oversight committee or a committee of peers would be helpful to add credence to reasons for schedule slippage.

We are working on a final report of the 1995 test at Bonneville which will conclude that there were no significant differences among sound-on and sound-off treatments: neither in turbine passage nor numbers crossing the upstream end of the array, where flow was most parallel to the transducer array. However, conclusions must be tempered by the possibility that lateral flows at the face of the dam compromised the array. Between 1000 and 0200 hours, the distribution of smolt passage among intakes was strongly skewed across the transducer array. This distribution supports the suggestion of flow bias. By contrast, the 24-hour distribution of passage was not skewed across the array, suggesting that flow bias was not a problem.

DR. TURNPENNY: When we are thinking about the evaluation of acoustic barriers, I think it's important to consider quite a wide range of measurement techniques for this. And most commonly we take the simplest route. For instance, on a cooling-water system, counting the number of fish coming on the screens, sound-on, sound-off; putting a net at the back end of the turbine or the fish passage, and so on. I recently looked at some work carried out in the south of France on designing a system for hydrostations to get downstream migrants to go down the bypasses. They have a conventional arrangement of a surface slot on the side that fish are expected to go to. And they were testing a well-designed angled electrical barrier. It was an adequate barrier, it met the criteria for what I would call the expectations of the fish, e.g., swimming speed. They found it wasn't working just by releasing batches of fish and catching the ones in the bypass and the ones that went straight through the turbines. They then did some experiments using a very simple technique of float tagging. These were salmon smolts, and they were using a quill tag on a half meter of nylon thread. And whatever you might think of that technique and its effects on the behavior of the fish, 1 think it is one of those situations where if you get irrational behavior, you don't believe it. But in this case, they got rational behavior, and they learned that the fish were all coming down to the intake, to the barrier. They were following along the face of the barrier absolutely perfectly, but then they didn't like the hydraulics at the bypass. They got confused, went through the barrier, were stunned, and disappeared off downstream.

Now, the assumption would have been that the barrier wasn't working there. In fact, it was the hydraulic geometry of the bypass that wasn't working. They then put a nice hydraulically-faired entrance to the bypass, and suddenly they got 90% efficiency. So I think there's a message there somewhere.

MR. HOLSAPPLE: Since Ned Taft has elevated failures to an award-winning situation, I'm fully qualified to get up and speak. ESEERCO has been sponsoring fish-protection research for about 15 years. I would just like to point out that we have experienced ebbs and flows in attitudes toward behavioral protective schemes over that period. Changes in regulatory agency personnel lead to changes in regulatory opinions about fish protection. For example, the pendulum swings from closed-cycle coding, through screening, to passive behavioral barriers. This shifting makes it difficult to maintain a long-term research focus on any one protective scheme. I suggest that the negative market analysis for sonic fish-protective schemes discussed earlier can be mostly explained by the uncertainty associated with future regulatory acceptance, and not on the merits of the current study results.

Finally, I have not heard very much about the importance of water quality, primarily chemistry, in understanding the results of sonic fish-protective studies. So can we expect genetic stocks, e.g., estuarine vs. Great Lakes, to respond differently to sound? Can this explain why we have seen results here that suggest clupeids, even the same species, from different parts of the world respond in dissimilar ways to the same sound?

DR. COOMBS: Pollutants in the water can certainly affect sensory systems; in particular, superficially based sensory systems like the lateral-line system. Actually, Karlsen & Sand (1987) have shown us this nice effect of cobalt chloride on the lateral-line system which basically interferes with the calcium channels and knocks out the system. Other heavy metals will probably have similar effects.

MR. HOLSAPPLE: It was cobalt-chloride results that captured my attention. If you just look in New York State where we have the Great Lakes, the tidal Hudson River, the Finger Lakes, and saline estuaries, we have diverse water quality with the same species living there.

DR. BROWN: It's very difficult to influence fish in Boston Harbor because they're wearing rubber suits.

DR. POPPER: You asked why fish in different parts of the world do different things. In fact, there's every reason to think that a fish stocked from the south will be different than a fish from up here. They make different sounds that affect their sensory systems, which may or may not be relevant. But there are certain things like numbers of vertebrae that will be different. So there are all kinds of factors. In fact, the same species may be doing very different things. Sheryl is much more direct, but there are other factors.

MR. HOLSAPPLE: So when we evaluate the response of clupeids from somebody's system somewhere, we must keep in mind that it's somewhere under those voyeuristic characteristics and everything else, and it may quite different --

DR. POPPER: At least you need to know it. I was talking with Carl Schreck about some stuff we were doing with Tom Carlson on growth of salmon. And one of the questions I was asked was hatchery-raised versus wild-raised. I don't know the answer, but I think that is a question we all have to be aware of.

Closing Remarks

DR. CARLSON: I will provide two or three general comments about the workshop that I feel are important to remember. I tried to pull together people for this workshop from opposite ends of the spectrum in terms of their experience. And we've found ourselves talking about everything from pore sizes and lateral lines to market surveys for acoustic companies, and that seems to be a pretty broad range. But one of the things that also emerged is the tremendous range among the various people here in understanding the different elements of this whole problem. One of the things I want to do is work with a subset of people here to develop a common understanding of terms that were used. In particular, trying to put a stake in the ground about what constitutes an acoustic field, what are some of the parameters, but moving it as far as possible from the wave equations and evolving it to the point where we start using common terms. So that, as we go to publish, as we build a support base for what we would like to do, as we extend our knowledge base, we can link-in better with other literature and discuss our problems with people in other disciplines, using terms that they understand so they can help us sooner and quicker.

DR. POPPER: First, on behalf of my colleagues who presented the tutorials, I want to thank Tom Carlson for inviting us to this very interesting and exciting workshop. While this will not necessarily be apparent from the written record of these proceedings, there is no doubt that all of us who approach issues from the viewpoint of basic science have developed a real appreciation for applied aspects of similar problems, and an interest in working with our counterparts in the applied areas to solve what are clearly problems of mutual interest.

What I have tried to do for these last few remarks is to come up with a list of things that we, as basic scientists, think we can contribute to long-range goals of solving fish passage problems. One of these areas is certainly an evaluation of the effects of sound stimuli on fish. We also have expertise in questions related to the morphology and function of the auditory system and lateral line, and how this affects signal detection.

Another important contribution that we can make is definition of the sound-detection and response capabilities of animals before a stimulus is tried in the field. For this, we need to do laboratory studies, including measuring audiograms, measuring parameters relative to localization, temporal analysis, etc.

Other areas that require a basic understanding of the biology of fish hearing as the basis for future applications of sound to control fish include the ontogeny of hearing capabilities and the nature of the sounds that normally elicit a behavioral response from fish in the wild. Issues of habituation need to be examined from the standpoint of basic science so that we can develop artificial stimuli that will result in least habituation to fishes of various sizes. Another question relates to the differences in responses to sound of hatchery vs. wild fish.

I will end by saying that what emerges from this discussion is a natural basis for interaction and synergy between people who are doing the laboratory-scale experiments and people taking more applied approaches to related problems. Working together, these investigators need to take the next step and go up one or two orders of magnitude to begin looking at the large-scale applied questions from the perspective of basic science, and go down a few orders of magnitude from large-scale studies and examine the issues raised there from the perspective of the basic biology of fish bioacoustics.

DR. NESTLER: First, I would like to say I really enjoyed the workshop, primarily because of the contrast that Art Popper and his folks brought to those of us who tend to work with large systems. It's been obvious to me for many years that that's the piece of the puzzle that really hasn't been there for us. I've watched fish, I won't tell you how many nights, obviously responding to stimuli generated by dams and screens and trash racks, and so on, and very obviously involving lateral-line systems.

But our panel, on reflection, was left with an odd feeling, because it seemed that half of the time that my panel was seated in the audience, we were being chastised for various inadequacies by the other panel. So some of what I am going to say is our response as a group to issues that were raised by members of the audience – good issues. I think, too, that when we do these applications of behavioral barriers, we need to characterize our systems as completely as we can and we need to be very sensitive to the statistical rigor and defensibility of our studies. Ultimately somebody is going to take a risk on the technology.

I certainly support the suggestion that we could obtain more credibility by increasing our interfaces with professional societies. Another question that arose was, what is the most appropriate use for behavioral barriers. And there seems to be a philosophy that behavioral barriers are a replacement or substitute for other kinds of systems, primarily physically-based systems. I think a good compromise that we spiralled into was that the role of behavioral barriers for now should be focused on sites where other kinds of systems are just not feasible, for whatever reasons, or to supplement or complement or enhance existing systems. Because ultimately, if you understand acoustics, it involves those same kinds of stimuli that are used to guide fish with conventional mechanical systems. So there is an opportunity there, I think.

We definitely need to increase our knowledge base. Many of the new developments seem sporadic, that it's not possible to really link them rigorously to some definite knowledge base or paradigm. There is a need to increase our communications within the scientific community, so that we can link this technology better with real biology and with real behavior. I guess an inference I made was that we perhaps need a standards committee, that there seems to be a lot of variability in application. And just by looking at these workshop presentations, there seemed to be some variability in application of the technology. Although this is probably a 'growing pain' because this area is in its infancy, maybe we need to think about standards of application.

A really interesting point was the need to build on negative results. We don't ordinarily present negative results, but I don't want you to think for a second that we're successful every time. But it's something that we really don't think of as professionals, because we typically have 5 minutes to present our results and, obviously, we want to present the positive results first. But I think for a field that's just in its infancy, we should concentrate on exchanging failures as much as successes, because I think the knowledge base will develop more quickly.

To me, this whole acoustical area is a huge opportunity in two ways. Obviously, we can develop sources and make some fish do what we want them to do. But it's also a way to understand fish behavior and to make the conventional technologies work better. I've watched video images of smolts bouncing across screens, thousands of them. From this, I know that screen technology also has its problems. I've also watched debris tracks on video images of screens. From the chaotic behavior of the debris particles, I'm convinced that the extremely high-energy hydrodynamics associated with water passing through screens are generating sound fields, and that is a component of screen design that causes some of the screens to perform the way they do. And right now that's a complete void, but it fits within this overall paradigm of guiding fish with sound. We don't understand it, we don't appreciate it, we're not aware of it, but we're doing it now (by accident).

DR. CARLSON: I want to thank everyone who came, particularly those who traveled far, and declare this workshop closed.

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Workshop Registrants

Stephen Ahern
De&e & Tarbell, Inc.
1814 NW 140th Circle
Vancouver WA 98685

Brian Allee
Harza Northwest Inc.
2353 130th NE, Suite 200
Bellevue WA 98005

Jim Atheam
North Pacific Division
Army Corps of Engineers
P.O. Box 2870
Portland, OR 97208

Curtis Bell
Dow Neurological Institute
1120 NW 20th Avenue
Portland OR97209

Gustavo Bisbal
Northwest Power Planning Council
851 SW Sixth Avenue, Suite 1100
Portland OR 97204-1348

Steve Brink
Idaho Power Company
P.O. Box 70
Boise ID 83707

John Brogoitti
Northwest Power Planning Council
11 SW Byers Street
Pendleton OR 97801

Ron Brown
Flash Technology
P.O. Box 1549
Brentwood TN 37024

Mike Burczynski
Army Corps of Engineers
Bonneville Lock & Dam
Cascade Locks OR 97014

Roger Campana
Jeff Condiotty
Simrad Inc.
19210 33rd Ave. West
Lynnwood WA 98036

Diana Carroll
Environmental & Technical Services Division
National Marine Fisheries Service
525 NE Oregon Street
Portland OR 97232-2737

Deborah Carter
Habitat Conservation Branch
Environmental & Technical Services Division
National Marine Fisheries Service
525 NE Oregon Street

Peter Christensen
Sverdrup Civil, Inc.
Sverdrup Corporation
3300 Carillon Point
Kirkland WA 98083

Doug Cramer
Portland General Electric (PGE)
33831 SE Faraday Road
Estacada OR 97033

Bob Dach
Portland District
Army Corps of Engineers
P.O. Box 2916
Portland OR 97208-2946

Dennis Dauble
Pacific Northwest National Laboratory
P.O. Box 999
Richland WA 99352

Michelle Day
Habitat Conservation Branch
Environmental & Technical Services Division
National Marine Fisheries Service
525 NE Oregon Street
Portland OR 97232-2737

Aaron Diaz
Imaging & Nondestructive Evaluation Group
Pacific Northwest National Laboratory (K5-26)
P.O. Box 999
Richland WA 99352

Dan Domina
Portland General Electric (PGE)
121 SW Salmon Street, 3WTC
Portland OR 97204

Edward Donahue
'Fish Pro/Beak Consultants Inc.
3780 Mile Hill Drive
Port Orchard WA 98366

Barry Doust
730 Toftrees Ave. #316
State College PA 16803

Blaine Ebberts
Portland District
Army Corps of Engineers
P.O. Box 2946 (CENPP-PE-E)
Portland OR 97208-2946

Jim Evan
Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg MS 39180

John Ferguson
Portland District, Army Corps of Engineers
P.O. Box 2946 (CENPP-PE-E)
Portland OR 97208-2946

Mike Gessel
Northwest Fisheries Science Center
National Marine Fisheries Service
3305 E. Commerce Street
Pasco WA 99301-5839

Al Giorgi
Don Chapman Consultants
7981 168th Ave. NE
Redmond WA 98052

Frederick A. Goetz
Seattle District
Army Corps of Engineers
P.O. Box 3755
Seattle WA 98124-2255

Mike Haberland
Public Service Electric & Gas (PSE&G)
P.O. Box 236 (M-C N33)
Hancocks Bridge NJ 08038

Steve Hays
Chelan County P.U.D.
P.O. Box 1231
Wenatchee WA 98801

James Henderson
HT&T
9320 NE Day Road
Bainbridge Island WA98110

John Holsapple
ESEERCO
5172 Western Avenue Turnpike
Altamont NY 12209

Becky Hough
Department of Biology
University of Portland
5000 N. Williamette Blvd.
Portland OR 97203-5798

Larry Jansen
Portland State University
5706 SE Clinton Street
Portland OR 97206

Gary Johnson
Pacific Northwest National Laboratory
P.O. Box 999
Richland WA 99352

Peter Johnson
Army Engineer Waterways Experiment Station
P.O. Box 241
N. Bonneville WA 98639

Robert Johnson
Pacific Northwest National Laboratory
P.O. Box 999
Richland WA 99352

Dan Kenney
Walla Walla District
Army Corps of Engineers
201 N. Third Street
Walla Walla WA 99362

Suzanne Knapp
Oregon Dept. of Fish & Wildlife
Route 2, **Box 2541**
Hermiston OR 97838

Chris Knutsen
Oregon Department of Fish & Wildlife
17330 SE Evelyn Street
Clackamas OR 97015

Steve Kucas
Dames & Moore
1750 SW Harbor Way, Suite 400
Portland OR 97201

Eddie Kudera
BioSonics Inc.
3670 Stoneway North
Seattle WA 98103

Kevin Kumagai
'Hydroacoustic Technology, Inc. (HTI)
715 NE Northlake Way
Seattle WA 98105

Walter Lanick
Bureau of Reclamation
P.O. Box 1749
Yakima WA 98987-1749

Larry Lawrence
Army Engineer Waterways Experiment Station
Bonneville Lock & Dam
Cascade Locks OR 97014

Randy Lee
Portland District
Army Corps of Engineers
P.O. Box 2946 (CENPP-PE-HD)
Portland OR 97208-2946

Mark Mattson
Normandeau Associates
25 Nashua Road
Bedford NH 03110-5500

R. Lynn McComas
Northwest Fisheries Science Center
National Marine Fisheries Service
3305 E. Commerce Street
Pasco WA 99301-5839

Lee Miller
Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg MS 39180

Sandra Meier
ESEERCO
5172 Western Turnpike
Altamont NY 12009

Edward Meyer
National Marine Fisheries Service
Environmental & Technical Services Division
525 NE Oregon Street (F/NWO3)
Portland OR 97232-2737

Ron Morinaka
Bonneville Power Administration
P.O. Box 3621
Portland OR 97208

Bill Nagy
Army Corps of Engineers
Bonneville Lock & Dam
Cascade Locks OR 97014

Ed Nunnallee
Northwest Fisheries Science Center
National Marine Fisheries Service
P.O. Box 130
Manchester WA 98353

Steve Parker
Yakama Indian Nation
P.O. Box 151
Toppenish WA 98948

Robert Pearce
Summit Technology, Inc.
1535 NW 130th Avenue
Portland OR 97229

Mark Plummer
Walla Walla District, Corps of Engineers
Ice Harbor Dam Project Office
Route 6, Box 693
Pasco WA 99301

J. Darrell Pock
Grant County PUD No. 2
P.O. Box 878, 30 C Street SW
Ephrata WA 98823

Pat Poe
Bonneville Power Administration
P.O. Box 3621
Portland OR 97208

Michael Powelson
Northwest Power Planning Council
620 SW Fifth, Suite 1025
Portland OR 97201

Earl Prentice
Northwest Fisheries Science Center
National Marine Fisheries Service
P.O. Box 130
Manchester WA 98353

Bruce Ransom
Hydroacoustic Technology, Inc. (HTI)
715 NE Northlake Way
Seattle WA 98105

Lynn Reese
Walla Walla District, Army Corps of Engineers
201 N. Third Street
Walla Walla WA 99362

Dave Reitz
GRD Associates
13005 NE Third Place
Bellevue WA 98005

John Rowan
'Army Corps of Engineers
P.O. Box 3621,
Portland, OR 97208

Sharon Sawdey
FishPro/ Beak
317 SW Alder, Suite 800
Portland OR 97204-2583

Marvin Shutters
Portland District, Army Corps of Engineers
P.O. Box 2946
Portland OR 97208-2946

Mark Smith
Portland District, Army Corps of Engineers
P.O. Box 2946 (CENPP-PE-E)
Portland OR 97208-2946

William Spurgeon
Walla Walla District, Corps of Engineers
Lower Monumental Project Office
Route 6, Box 693
Pasco WA 99301-9165

Jodi Stroklund
Bonneville Power Administration
P.O. Box 3621-EWN
Portland OR 97208

Charles Sullivan
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto CA 94304-1395

Robert Sullivan
Parametrix Inc.
5808 Lake Washington Blvd. NE, Suite 200
Kirkland WA 98033-7350

Rudd Turner
North Pacific Division
Army Corps of Engineers
P.O. Box 2870 (ET-PR)
Portland OR 97208-2870

Paul Wagner
Washington Department of Fish & Wildlife
500 N. Morain, Suite 12008
Kennewick WA 99336

Rick Wantuck
National Marine Fisheries Service
777 Sonoma Boulevard, Rm. 325
Santa Rosa CA 95404

Michael Ward
Terraqua Environmental Consulting
30307 H Street
Ocean Park WA 98640

Gary Weeks
Trotters Shoals Limnological Research Facility
Calhoun Falls SC 29628-0533

Cliff Whitmus
Pentel
120 Third Avenue South, Suite 110
Edmonds WA 98020

Joanne Wu
Habitat Conservation Branch
Environmental & Technical Services Division
National Marine Fisheries Service
525 NE Oregon Street
Portland OR 97232-2737

Garwin Yip
Habitat Conservation Branch
Environmental & Technical Services Division
National Marine Fisheries Service
525 NE Oregon Street
Portland OR 97232-2737

Randy Zelick
Department of Biology
Portland State University
P.O. Box 751
Portland OR 97207